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Farmer Responses to Solar Irrigation in India Agent-Based Modeling to Understand Sustainable Transitions

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CSTEP CENTER FOR STUDY OF SCIENCE, TECHNOLOGY & POLICY

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About the Organizations

International Water Management Institute (IWMI)

IWMI is a research-for-development (R4D) organization, with offices in 14 countries and a global network of scientists operating in more than 30 countries. For over three decades, our research results have led to changes in water management that have contributed to social and economic development.

IWMI's Vision, reflected in its Strategy 2019-2023, is 'a water-secure world'. IWMI targets water and land management challenges faced by poor communities in developing countries, and through this, works towards the achievement of the Sustainable Development Goals (SDGs) of reducing poverty and hunger and maintaining a sustainable environment.

Solar Irrigation for Agricultural Resilience

The Solar Irrigation for Agricultural Resilience in South Asia (SoLAR-SA) project aims to sustainably manage the water-energy and climate interlinkages in South Asia through the promotion of SIPs. The main goal of the project is to contribute to climate-resilient, gender-equitable, and socially inclusive agrarian livelihoods in Bangladesh, India, Nepal and Pakistan by supporting government efforts to promote solar irrigation. This project responds to government commitments to transition to clean energy pathways in agriculture. All countries in this project have NDC commitments to reduce GHG emissions and SIPs can play a significant role in reducing emissions in agriculture.

Swiss Agency for Development and Cooperation

The SoLAR -SA project is supported by the Swiss Agency for Development and Cooperation (SDC). SDC is the agency for international cooperation of the Federal Department of Foreign Affairs (FDFA). Swiss Agency for Development and Cooperation, which is an integral part of the Federal Council's foreign policy, aims to contribute to a world without poverty and in peace, for sustainable development. SDC, through its Global Programme Climate Change and Environment (GPCCE), helps find solutions to global challenges linked to climate change. It engages in global political dialogue and manages specific projects in the fields of energy, climate change adaptation, sustainable development of mountainous regions and prevention of natural hazards that are likely to influence regional and international policy.

Water, Environment, Land and Livelihoods (WELL) Labs

Water, Environment, Land and Livelihoods (WELL) Labs co-creates research and innovation for social impact in the areas of land and water sustainability. It is a new center based at the Institute for Financial Management and Research (IFMR) Society. Together with Krea University and other centers at IFMR, such as the Abdul Latif Jameel Poverty Action Lab (J-PAL) South Asia and Leveraging Evidence for Access and Development (LEAD), WELL Labs is part of an ecosystem of labs and research centers with a mission to help prepare for an unpredictable world.

Ashoka Trust for Research in Ecology and the Environment (ATREE)

The Ashoka Trust for Research in Ecology and the Environment (ATREE) is a global non-profit organization that generates interdisciplinary knowledge to inform policy and practice towards conservation and sustainability. For over two decades, ATREE has worked on social-environmental issues at local policy levels. ATREE envisions a society committed to environmental conservation and sustainable and socially-just development.

Center for Study of Science, Technology and Policy (CSTEP)

The Center for Study of Science, Technology and Policy (CSTEP) is one of India's leading think tanks, with a mission to enrich policymaking with innovative approaches using science and technology for a sustainable, secure and inclusive society. Their work is in the areas of climate, environment, sustainability, energy, AI for social impact and new materials. The research leverages innovative technology-based ideas to solve developmental challenges and their vision is to be the foremost institution for policy analysis in India.

List of Contents

Executive Summary

Solar irrigation is being promoted in India to address the twin problems of irrigation access and groundwater overexploitation. However, the potential impacts of this step are not fully understood. A majority of the farmers in India depend on rainfall for their livelihoods because they lack access to irrigation. They are completely dependent on the rains, making them more vulnerable to climate variability. They also only get a single crop during the monsoon; their land is unproductive for most of the year. There is a looming crisis of rapid depletion of groundwater threatening farmers who access wells to irrigate their land.

Solar irrigation has the potential to address both these problems. Firstly, it increases access to irrigation by providing energy to farmers who are not connected to the grid or use expensive diesel pump sets. Secondly, it also works to curb groundwater abstraction through net metering, where farmers can draw the groundwater, they need to irrigate and sell the excess electricity back to the grid and earn money through feed-in tariffs (FiTs). However, the net impact on groundwater is unpredictable because it depends on farmers' crop choices.

There have been some empirical studies on the impacts of solar irrigation, but the results are applicable only to the specific pilots. Often the conditions – biophysical, socioeconomic and policy incentives – under which pilots are conducted are not replicable. There was also an expressed need from policymakers for 'what if' analyses that might predict what might happen under different conditions.

To address this, we applied an agent-based modeling (ABM) approach to understand farmer choices and transitions before and after solar irrigation in select districts, that entailed the following:

- We developed a framework to predict how agents behave based on resource limits and incentives and classified regions based on this:
    - resource limits, which refer to land, energy and water-related constraints that individual farmers face.
    - incentives, which refer to the price guarantee they get for the crops they produce, and their perceptions of risk.
- We estimated farmers' net present value, irrigation water requirements and economic and cultural risks to identify possible options that are available.
- We interviewed experts to seek plausible transition options, and to validate options from the modeling exercise.
- Finally, we plotted the most plausible outcome in the districts under study.

Both our agent-based model and expert consultations suggest that sustainable transitions – changes in crop choices that are both profit maximizing and have less irrigation water requirements – are physically and theoretically possible. However, in practice, the introduction of solar irrigation under assumed conditions is unlikely to result in major crop transitions across the districts we studied. This is because there are deep lock-ins in agriculture where farmers and the entire ecosystem that they operate in are tied to certain production techniques and choices that they are unlikely to break out of. Additionally, biophysical constraints on land and water also limit choices.

Here are our key learnings from the six case studies:

1. In **Bathinda, Punjab**, farmers are likely to continue growing paddy-wheat and cotton-potato, given strong government procurement systems. A sustainable transition to a less water-intensive crop will require the setting up of strong market linkages for alternatives like kinnow (a citrus tree). Otherwise, the groundwater status in most parts of the district will continue to remain critical and overexploited.
2. In **West Champaran, Bihar**, we assumed that solar irrigation is likely to replace diesel pump sets. Since we also assumed that they are not connected to the grid, there is no income earned from the sale of energy to the grid. Here too, farmers are likely to continue with current cropping systems, with the inclusion of a third summer crop like minor pulses, which results in a marginal increase in income and abstraction. However, aquifers in most parts of Bihar have not been overexploited yet, which means continuing current cropping systems can still be viewed as a sustainable choice. It is also important to note that adoption of solar may not happen if it reduces income levels compared to current incomes, as is likely to happen in the case of sugarcane farmers.
3. In **Bengaluru Rural, Karnataka**, finger millet (*ragi*) farmers are likely to switch over to agrivoltaics (sale of solar power with no associated irrigation), if subsidized, while arecanut farmers will continue growing it given its strong private procurement system. Most parts of this district have been categorized as critical and overexploited. Switching from water-intensive crops like arecanut, rice and sugarcane will be critical to ensure groundwater sustainability.
4. In **Anand, Gujarat**, the dairy industry dictates the crops grown. In addition to current crop choices, we are likely to see the inclusion of a third summer crop for fodder. Groundwater levels in most parts of the district have been rising; hence continuing to grow current crops is likely to be sustainable.
5. In **Botad, Gujarat**, farmers grow a combination of cotton and groundnut during *kharif* (autumn) season. Changing this combination, in addition to growing wheat

or chickpea in the *rabi* (spring) season is likely to keep the district's groundwater status sustainable. Agrivoltaics are also a real possibility in this district.

6. In **Nadia, West Bengal**, farmers grow rice across all three seasons, and are likely to switch over to growing rice during *kharif* and lentils in the *rabi* seasons. This is a far more sustainable option compared to the present cropping pattern as the water requirement declines drastically and farmers may be able to earn better by switching from rice to other crops like lentils.

While solar irrigation offers options to circumvent the political non-feasibility of doing away with some policies pertaining to agriculture (Minimum Support Price – MSP) and energy (free or highly subsidized electricity), it will still be inadequate to change farmers' crop choices. But the situation is not hopeless. For solar irrigation to result in crop diversification and the cultivation of crops that fit in the water budgets of specific regions, sociotechnical evolutions also need to occur concurrently. This means that the entire system ranging from preproduction to consumption will have to evolve for true change to take effect. Changes in agricultural policies, such as the introduction of MSP for less water-intensive crops, and energy policies, such as the removal of electricity subsidies that allows farmers in states like Punjab free or highly subsidized access to the grid, can pave the way for truly impactful and long-lasting change stemming from the introduction of solar irrigation.

To our knowledge, this is the first research study that has attempted to apply ABM in the context of solar irrigation and its likely impact on farmers' incomes and groundwater sustainability in India. Given that there are opportunities and constraints that vary widely across states, it is critical to closely examine local contexts and apply the ABM approach to accurately gauge where solar irrigation can make a significant difference rather than force-fitting such schemes in regions where it could result in exacerbating current precarity.

In this report, we first lay out the context for why solar irrigation was introduced in India and why it was envisioned to tackle the challenges related to irrigation access. This section also outlines the current policy framework before going into the methodology followed to simulate the impacts of solar irrigation on farmers' behavior. We then describe six case studies that illustrate the possible impact of solar irrigation on irrigation water requirement and farmer incomes.

1. CONTEXT

1.1 Indian agriculture is plagued by overexploited and scarce groundwater

India faces a looming groundwater overexploitation crisis. This is particularly of concern to the agriculture sector, the largest user of groundwater resources in the country. Policies favoring the growth of staple water-intensive cereal crops in different states have played a key role in irrigation expansion (Devineni et al. 2022). Of the farmers using irrigation in the country, 70-80% are groundwater dependent, and more intensive irrigation frequently (but not always) means more income. Farmers use electricity (usually free or highly subsidized) to pump groundwater to irrigate their fields. As of 2017, 1,499 out of 6,881 units (blocks/mandals/taluks) assessed for groundwater fell under the category of 'overexploited'[1] or 'critical', covering areas in the states of Tamil Nadu, Telangana, Rajasthan, Uttar Pradesh, Haryana and Punjab (CGWB, 2017). Even as groundwater is being overexploited, half the smallholder farms in India, with less than two hectares (ha) of land (~five acres) are still rainfed and have no access to irrigation. This directly threatens the incomes and livelihoods of smallholder farmers as they are vulnerable to the vagaries of the monsoon.

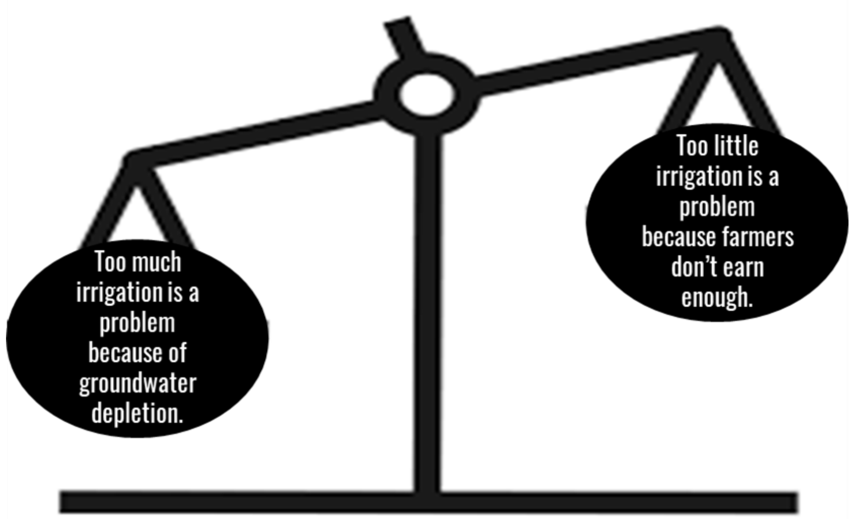

Figure 1. The Goldilocks dilemma.

Water managers thus face the Goldilocks dilemma in getting irrigation just right (Figure 1). On the one hand, policies aim to extend irrigation access to rainfed farmers, who account for half of India's farmers. Diesel pumps are expensive and constrain

[1] 'Overexploited' refers to the stage of groundwater extraction at 100% and critical implies extraction that is between 90% and 100%.

pumping, especially since the withdrawal of diesel subsidies in 2014. On the other hand, new policies like Pani Bachao Paise Kamao[2] in Punjab and Atal Jal Yojana[3], being introduced in seven states, aim to control groundwater overexploitation.

Originally introduced in the 1990s, solar irrigation gained popularity from 2009 onwards when solar panels became more affordable for farmers – the cost of solar photovoltaic (PV) panels dropped by almost 80% over this period, fueling demand. This decrease in cost has been associated with technological advancement and economies of scale. As more manufacturers started producing it, the modules got cheaper (Toussaint 2020).

In India, in areas where irrigated farming is widespread, farmers viewed solar pumps as a potential alternative to existing irrigation options, i.e., electricity sourced from the grid and diesel-powered pumps, for two important reasons:

- **'Free power':** For those who had access to rationed grid-connected electricity, this was 'additional free power', and for those without grid access it was 'free power' that could be used in lieu of or to supplement diesel pumps. Central and state governments together subsidize solar irrigation by up to almost 70% of the initial capital and installation costs.
- **Uninterrupted daytime power:** Since electricity is free or heavily subsidized, governments typically introduce an element of control by restricting the number of supply hours. In most cases, they provide electricity for four to eight hours per day, but it is not always clear when supply will be available. Stakeholder consultations across multiple regions in the country suggest that farmers most often leave their pump sets on all through the day and night.[4]

  Solar panels solve this issue of interrupted supply; farmers can now access a decentralized power source that is within their control. Apart from using solar pumps to irrigate their own fields, farmers continue to pump more water from the ground and sell it to their neighbors or lease rainfed land from neighbors.

The last decade thus saw a massive expansion of solar-powered irrigation. This could be because of the Government of India's ambitious target to increase renewable energy capacity in India. The number of solar irrigation pumps increased from less than 4,000 in 2012 to more than 237,120 as of September 2022 (Durga et al. 2021).

The central government launched the Pradhan Mantri Kisan Urja Suraksha evam Utthaan Mahaabhiyan (PM-KUSUM) in 2019 to improve the country's energy security,

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[2] Read more here: https://www.business-standard.com/article/pti-stories/paani-bachao-paise-kamao-campaign-launched-118062500857_1.html
[3] Read more here: https://ataljal.mowr.gov.in/
[4] Read more here: https://blogs.worldbank.org/energy/will-sun-god-answer-poor-farmers-prayers-or-make-things-worse

while increasing the installed capacity of electric power from nonfossil fuel sources. The scheme supports the installation of the following three components (PIB 2021):

- Component A: Addition of 10,000 megawatt (MW) of solar capacity through the installation of small solar power plants of capacity up to 2 MW;
- Component B: Installation of 20 lakh standalone solar-powered agricultural pumps; and
- Component C: Solarization of 15 lakh existing grid-connected agricultural pumps.

This report focuses on components B and C to understand the impact of either standalone or grid-connected farmer-owned and operated solar irrigation pumps on groundwater tables.

It is important to note that solar irrigation is not cheap or provided for free to farmers under these schemes. While there are practically no operations and maintenance costs, the farmer's contribution of 30% is significant. However, many states also buy back electricity allowing the capital cost to be recovered through income earned from the sale of excess electricity back to the grid. However, the payment process for the sale of excess energy back to the grid has still not been deployed at scale. It's not smooth and very few farmers are fully aware of this process, which is why adoption is slow. In most states, it is still at a pilot stage.

1.2 **Solar irrigation may reduce groundwater abstraction through feed-in-tariffs (FiTs)**

The impact of solar irrigation on water resources is more complicated because solar irrigation policies simultaneously aim to increase groundwater use in water-abundant regions and decrease its use in regions where it is overexploited.

Solar irrigation policies handle the dual objectives by allowing farmers to sell excess electricity back to the grid via a feed-in-tariff. This enables access to irrigation but also incentivizes water conservation, which in turn would help sustain the rapidly depleting groundwater table. For instance, the state government of Gujarat launched the Suryashakti Kisan Yojana (SKY) scheme in 2018 (Saran 2018)[5]. In the pilot phase, the scheme involves installation of solar PV plants on farmland connected to the grid. Farmers participating in the scheme pay 5% of the capital cost, with 60% of the remaining costs completely subsidized by the state and central governments. The power generated is for captive consumption, and any excess power can be sold to the state distribution company (DISCOM) at a tariff of INR 3.5 kilowatt hours (kWh) under a

[5] Read more here: https://bridgetoindia.com/gujarat-aims-for-the-sky/

25-year power purchase agreement. In addition to this tariff, the state government has offered an additional tariff of INR 3.5 kWh for the first seven years of the scheme.

1.3 Anticipating groundwater depletion with solar irrigation policies is a question of supply and demand

The sustainability of groundwater abstraction (whether within safe limits or overexploitation) depends on both the sustainable yield of the aquifer and amount of abstraction, which in turn hinges on factors such as crops grown and irrigation efficiency. For instance, if finger millet were to be grown in an area with low rainfall and consequently low recharge rates, it is likely to ensure sustainable abstraction of groundwater. However, growing arecanut instead might result in unsustainable abstraction rates as arecanut requires significantly more water than finger millet.

Solar irrigation does not *guarantee* a cap on abstraction. Rather, it makes an assumption about how much farmers value groundwater and *anticipates* abstraction. If the assumptions are incorrect, so will be the predicted outcomes. Therefore, in the context of solar irrigation, this requires understanding the price elasticities of groundwater consumption, i.e., how changes in demand for groundwater affect the price of groundwater itself. An accurate estimate of price elasticity will allow state DISCOMs to determine effective FiTs that serve as an incentive for groundwater savings. It also requires an understanding of geology and the constraints it poses. Further, this estimation needs to be frequent so that FiTs keep pace to limit abstraction over a period of time.

1.3.1 Understanding groundwater demand

Market forces drive demand: Let us begin with the theoretical demand curve for groundwater used for irrigation (Figure 2). The demand curve for any product or service is easy to develop when the price and the quantity demanded are clear – as happens when there are formal markets for a product or service. The problem is that we do not have a clear sense of where the demand curve lies because groundwater is not bought or sold directly; rather we have to infer how valuable it is to farmers based on what they grow and how much profit they are able to earn from it. As a first step, it is critical to determine where the curve lies as accurately as possible and the price elasticity of groundwater consumption for irrigation relative to the price of groundwater, particularly as agricultural markets are also not well functioning in India.

It must be noted that what we call the price of groundwater (even in places where there is a price) is merely the sum of pumping and any transportation costs, which is much lower than its true scarcity value[6] –it doesn't account for what groundwater might be

[6] A mathematical model by Ghosh and Bandyopadhyay (2009) as cited in Ghosh (2022) defines the scarcity value of water as the marginal value loss due to the scarcity of water. The magnitude of the loss is a metric of the degree of deprivation and creates the basis for water conflicts. (https://www.orfonline.org/research/water-scarce-economies-and-scarcity-values/)

priced at if a market for it existed or how much loss would be sustained by the economy if groundwater were to disappear.

Regulatory factors constrain demand: Today, groundwater In India is 'open access', anyone with a pump is legally allowed to abstract it. Further, the electricity that is used to pump this water from the ground is free or subsidized. This 'perverse incentive' has resulted in over abstraction of groundwater. Farmers, after taking as much as they need, often pump more to store on the surface in ponds or tanks or sell to their neighbors (Mukherji 2020)[7] In some cases, access to unrestricted groundwater has also caused changes in cropping, with farmers adopting more high-value water-intensive cropping patterns. For instance, in Bengaluru Rural and Tumkur districts of Karnataka, access to borewells or water tankers has resulted in a substantial increase in arecanut cultivation[8].

1.3.2 Understanding groundwater supply

The nature of the supply curve depends on both the aquifer type as well as the policies surrounding abstraction.

Hydrogeological factors constrain supply. In Punjab, groundwater is held in massive alluvial aquifers that economists sometimes call 'bathtub aquifers' (Figure 2). In such a system, each farmer's pumping has a relatively small impact on the water table, as water moves across the aquifer system. In contrast, large parts of peninsular India have a hard rock aquifer, much like an egg carton. This means that they are fast responding and local. During rain deficit years, they quickly run out of water and during rain surplus years, they fill up equally quickly. Most hard rock regions in peninsular India tend to behave like egg cartons.

Figure 2. Bathtub versus egg cartoon aquifers [Image credit: USGS][9].

[7] For more details, see Mukherji (2020): https://onlinelibrary.wiley.com/doi/full/10.1002/aepp.13123
[8] Based on ATREE field work in the region.
[9] This analogy was first put forward by Beattie (1981). Srinivasan (2022) gives a simple explanation of these aquifers and their behavior.

To make the situation more complicated, there is currently no way to estimate what the sustainable yield is – it is likely to vary depending on several factors including the type of aquifer, rainfall and other sources of recharge. While we know that the current levels of groundwater abstraction are unsustainable, we do not know the exact point at which groundwater becomes overexploited. Different regions have different levels of water abstraction (water demand) and recharge through rainfall (water supply) and importantly, the supply curve for groundwater depends on the aquifer type.

Policy factors determine supply. Groundwater supply is also constrained by policy choices. There are two policy paradigms that constrain groundwater supply: rationing and pricing.

In a rationing paradigm, farmers receive a fixed allocation of water (by restricting electricity hours). Uncertainty in the demand curve means that the farmer might have a higher price of groundwater and, therefore, it has implications for farmer profits. Note that the term 'rationing' is from the farmer's perspective. It does not mean that sustainable abstraction is achieved. While there is a restriction on the number of hours of electricity available, the amount of water extracted during this period could still be higher than what is considered sustainable for that region, depending on the rainfall and geology. Thus, even a rationing system could be detrimental to groundwater sustainability since it doesn't set limits on the amount of water that can be abstracted based on the resource endowment.

In contrast, in a pricing paradigm, the price of water for farmers is fixed, but if the demand curve is unknown, the quantum of groundwater that will be abstracted is uncertain. This is the underlying motivation for our study – to understand how moving to this new pricing paradigm, under solarization, will impact groundwater.

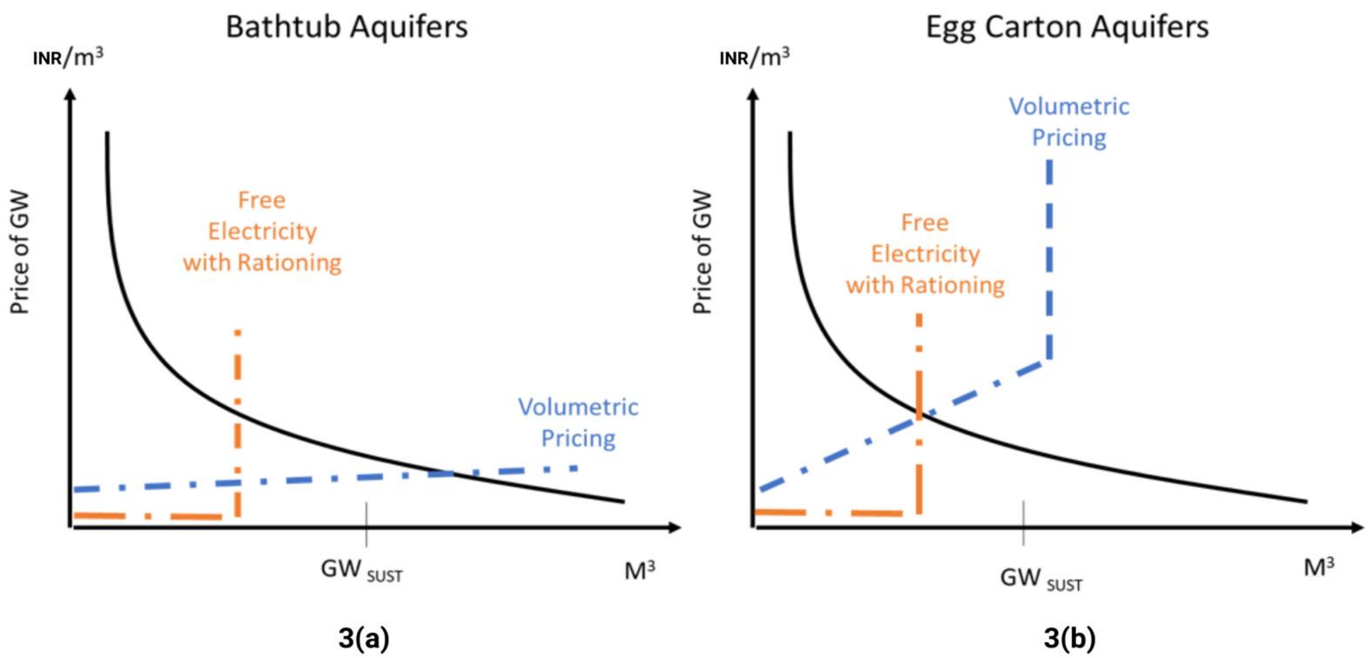

Figure 3. Theoretical demand and supply curves for groundwater (GW). The blue lines refer to a pricing regime (possibly, with solar irrigation) and the orange lines refer to a rationing regime (with free electricity and restricted hours of supply).

In the 'seemingly endless' bathtub aquifers of the Indo-Gangetic plains, farmers, for most part, are not yet feeling the pinch of groundwater decline (Srinivasan 2022), or at least they do not experience it within a cropping season. Even in low rainfall years, they do not face a sudden decline in availability. Thus, farmers in Punjab can continue growing water-intensive crops like rice and wheat (that have stable markets underpinned by the MSP), without being affected by declining groundwater tables (Figure 3a). If power is priced, farmers will experience some increase in pumping cost as a local cone of depression forms, but it will be small. Since the water tables fall relatively slowly (less than a meter/year), farmers simply drill deeper and switch to pumps with higher capacity every few years. In other words, the short-term groundwater supply curve is almost a horizontal line in the short to medium term. However, if power is free but rationed, then farmers are going to experience a limit on abstraction.

In contrast, in the egg carton aquifers in peninsular India, groundwater availability tends to constrain irrigation in the dry season *within the same year*, as availability depends on the extent of local recharge during the monsoon. Such aquifers tend to be local, and farmers can easily run out of water for the second crop if they grow water-intensive crops or don't adjust cropping in a dry year. If groundwater is metered and priced with a volumetric tariff, the supply curve will rise until groundwater is depleted, when it becomes a vertical line (Figure 3b).

To understand the impact of solar irrigation, it is important to account for these regional variations in aquifer types that affect the groundwater supply curve While it may seem that solar panels represent 'free electricity', farmers do take a loan for the solar panels and have the choice and incentive to sell the electricity back. The fact that the electricity can be sold, effectively means that groundwater abstraction has an opportunity cost and is therefore 'priced'. Thus, solar irrigation represents a shift from a 'rationing paradigm' (providing free electricity use for a few hours a day) to a 'rationing plus pricing paradigm' (allowing farmers to access as much as they want but at a cost and only during sunshine hours).

The current paradigm of solar irrigation involves distinct policy choices in terms of subsidy levels, directionality and feed-in-tariffs, which determine abstraction outcomes.

Subsidy, directionality, feed-in-tariffs and maximum permissible horsepower are some of the specifics that make up the PM-KUSUM scheme.

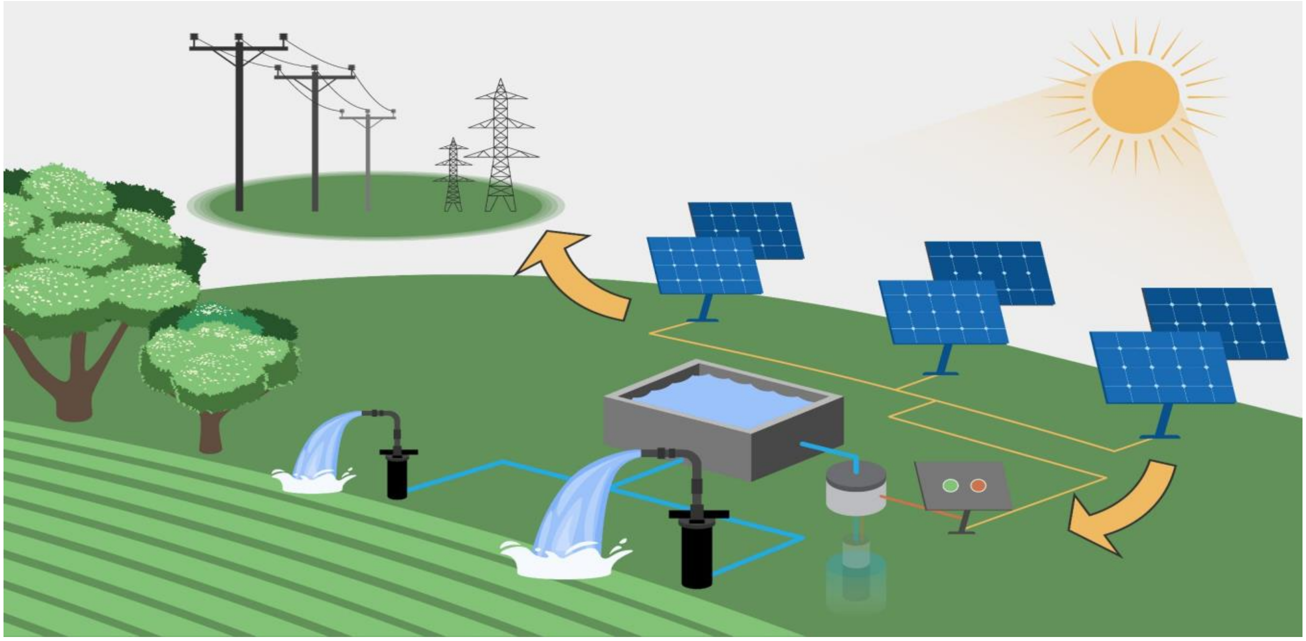

Figure 4. Solar irrigation system with net metering. Illustration by Aparna Nambiar.

Individual farmers having grid-connected agriculture pumps will be supported to solarize pumps. They will be able to use the generated solar power to meet their irrigation needs and the excess solar power will be sold to DISCOMs. A simple illustration of this set up is provided in Figure 4.

Allowable HP. Solar PV capacity up to two times the pump capacity in kW is allowed under the scheme. Thus, a farmer with a 2 horsepower (hp) (1 hp = 746 W) pump can get a solar panel with a capacity of up to 1.5 W. Since financial assistance from the central government is capped at 7.5 hp pump capacity, a farmer with a 10 hp pump can still solarize, but only 15 kW will be eligible for the central government's subsidy. States have no such limit; the pump capacity is at the discretion of the states.

Subsidy rate. The solar panel may be provided to the farmer at a subsidized rate. Both the state and central governments may provide subsidies independently. For example, the central government will subsidize 30-50% of the benchmark cost or the tender cost, whichever is lower, of the solar PV component to be provided. The state government will give a subsidy of 30% and the farmer has to pay the remaining sum. Financial support in the form of bank loans may be made available to help farmers with their contribution.

Directionality. The solar irrigation system can be connected with the utility power grid through a bidirectional or unidirectional meter. If the meter is bidirectional, then the farmer can use electricity from the grid and, also sell it back and is charged for the 'net electricity used/sold'. The price of electricity may be different in both directions. If the meter is unidirectional, then the farmer can only sell electricity back to the grid and not use electricity from it.

Feed-in-tariff. Feed-in tariff is the fixed electricity price that is paid to the farmer for each unit of energy produced and injected into the electricity grid from the solar irrigation system.

1.4. The case for solar irrigation: Decarbonization, economic and resource sustainability

From an economic perspective, solar irrigation offers farmers an additional and reliable source of income earned from the sale of excess electricity back to the grid. Replacing 10 lakh diesel pump sets across the country with solar irrigation pump sets could result in savings for the farmer as well, since diesel subsidies have been withdrawn[10].

From an environmental perspective, solar irrigation could potentially reduce CO_2 emissions by up to 25.3 million tonnes annually by both reducing direct use of diesel as well as coal-powered electricity accessed through the national grid (Durga et al. 2021).

The impact of solar irrigation policies is not trivial. Many state governments are interested in understanding how it will impact farmer income and sustainability of water resources. Presumably, the net outcome will depend both on the biophysical conditions in each state and the design of solar irrigation policies, in addition to prevailing agricultural practices and perhaps a change in practices linked to freely available groundwater.

[10] Feasibility Analysis for Solar Agricultural Water Pumps in India. January 2014. KPMG + Shakti Sustainable Energy Foundation.

2. CONCEPTUAL FRAMEWORK AND MODEL

2.1. Empirical data collection is not enough, we also need simulation models

Relying on empirical insights alone to understand the full and expected impacts of solar irrigation on farmers' choices and incomes, and a region's groundwater sustainability may not be enough for three reasons:

- Many of these initial schemes are 'gold-plated'. Since they are pilots, a lot of the emphasis has been on working out the kinks and demonstrating feasibility. As a result, the insights obtained from these schemes may not be scalable when some of the more favorable terms are rescinded (such as subsidies or feed-in-tariffs).
- The biophysical and socioeconomic conditions under which the pilot schemes are implemented may be unique. Farmer behavior under these conditions may be different from that in the states in which the schemes may eventually be implemented.
- The initial insights emerging from these pilots suggest that farmers take a few years to understand how the schemes work and trust that the payments for FiTs will be made on time. However, once this occurs there may be a shift in farmer behavior to change cropping patterns or irrigation technologies, which may not manifest in the initial phases of the scheme's implementation. Such shifts or adaptive behavior is commonly observed in other policies like the introduction of drip subsidies or lift irrigation schemes.

Thus, the empirical insights from the pilot schemes, while indicative, may not be sufficient to understand what could happen when solar irrigation is scaled. The only way to do this is to simulate possible scenarios of how farmers might behave and the outcomes that may emerge under different policies.

Simulations can offer an ex-ante view into potential outcomes. Simulations are an imitation of the real world and built on a model. As we run experiments and change some variables, all the outputs change as well. Simulations are often quicker and a less expensive way of understanding potential impacts of interventions. For instance, crop simulation models are conducted extensively across many countries to understand the full impacts of crop inputs on crop yield. They are then used to make changes around input choices at a farm or plot scale[11]. These simulation exercises have become even more important and common in the light of climate change. Planners want to understand the impact climate change will have on crop cultivation, yield and

[11] Read more here: https://www.sciencedirect.com/science/article/pii/B9780444525123002333

subsequently, the food and nutritional security of the country. There are various types of simulations, and agent-based modeling is one such type.

2.2. An agent-based modeling framework simulates how solar irrigation impacts farmer behavior and groundwater abstraction

Agent-based models have a matrix of conditions and actions we want to understand. In this case, the conditions consist of regional constraints (biophysical conditions that make solar irrigation possible or not), policy design (implementation constraints) and agent constraints (land, energy and water), as shown in Figure 5.

Agent-based modeling has been used since the late 1990s for a variety of applications including modeling farmer behavior. One of the key differentiators with ABMs is the introduction of farm heterogeneity (differences in the types of farmers), spatial location, inclusion of interactions between farmers and consumers, the ability of agents to have adaptive capacity and learning possibilities and the ability to link these to biophysical models (Kremmydas et al. 2018). Recent applications of ABM include:

- Tamburino et al. (2019), who simulated a smallholder farming system to determine farmers' attitudes towards choice of water sources. This helped identify the most beneficial water source for the farmer's economic gain and stability, as well as the possibility of any tragedy of the commons.
- Sange et al. (2021), who simulated past adoption decisions of Indian farmers of various agricultural adaptation strategies to compare simulated behavior with observed behavior. This allowed researchers to understand decision-making rules and heuristics that drove some of the decision strategies.

Many studies have applied ABM and simulations for water resource management, irrigation planning, crop modeling and agricultural economics. To our knowledge, this is the first research study that has attempted to apply ABM in the context of solar irrigation and its likely impact on farmer behavior and groundwater sustainability.

We used ABM to understand what agent responses are likely to be in terms of crop choice and what the impact is on farmers' incomes and district-level groundwater use and status.

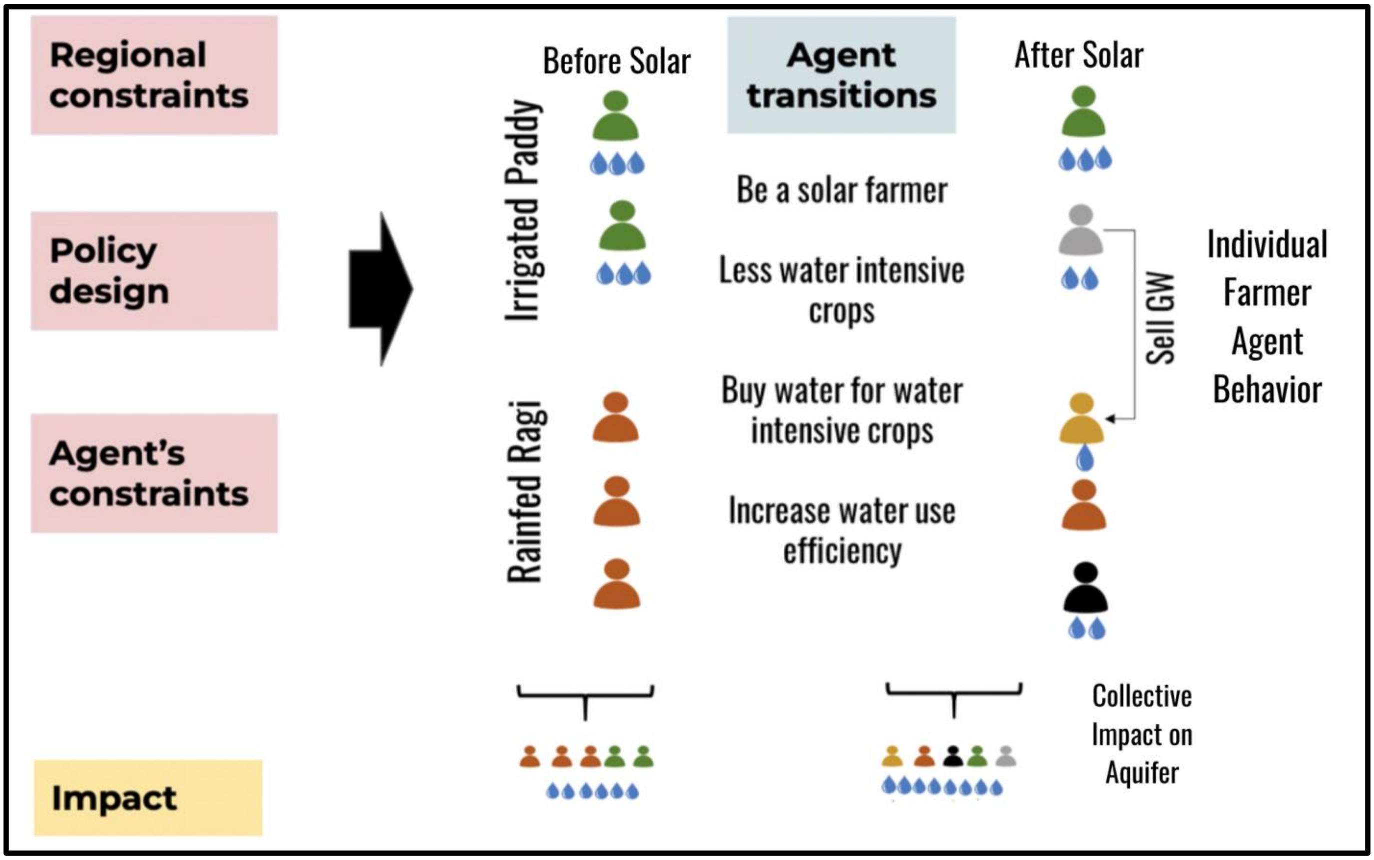

Figure 5. Linked agent-groundwater modeling framework.

The modeling framework is based on the premise that individual farmers make choices based on their own objective functions (maximizing profit, minimizing risk), subject to exogenous constraints on their decision making. We start with the individual representative farmer in a district (rainfed and/or irrigated) to understand their likely choice, and then we aggregate the decision for all the farmers in the district to then estimate the collective groundwater impact.

Agent decisions are constrained by resource limits as well as incentives available to them. So, we developed a typology to classify regions based on what constrains farmers.

The framework we used in this study assessed farmer behavioral transitions before and after solarization. We developed a biophysical typology of regions based on what constrains farmer choices -- whether these arise from policy or resource limitations (Figure 6). Every region (district/block/geographical area of study) can be broadly classified into having any one or more of these constraints: electricity, water and land. In the presence of these constraints, we wanted to understand how agents (farmers) are likely to behave both before and after solar irrigation.

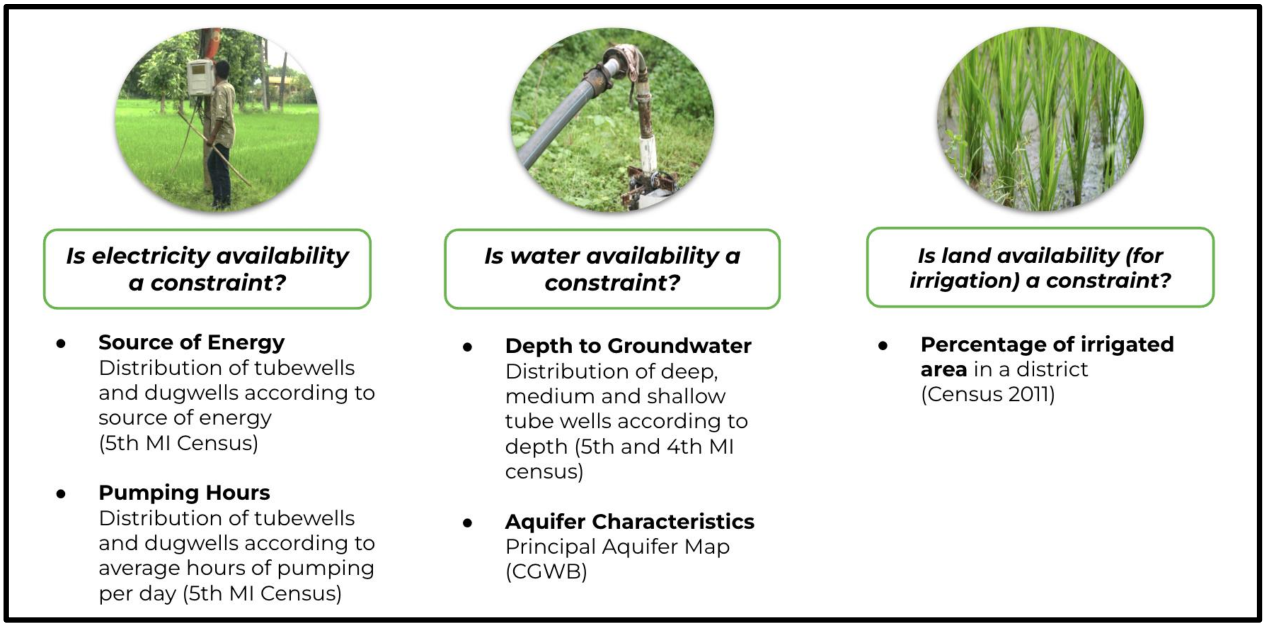

Figure 6. Electricity-water-land typology of farmer constraints.

These typologies determine what choices can be included in the choice set. For instance, if all the available land is being irrigated, leasing in rainfed land to expand irrigation is not a possibility.

Farmers make decisions based on the following:

- **Profit** -The profit earned from crop cultivation or solar electricity sale vis-a-vis investments.
- **Risk** - The economic risk associated with crop choice or sale of solar energy; and
- **Water use** - The farmer's irrigation water requirements for crops grown over the three seasons – *kharif (monsoon), rabi (post-monsoon), and zaid (summer)*).

One of the most important considerations is that farmers are not making decisions based on maximizing profit alone. They also seek to minimize risk.

The agent-based model accounts for the economics of farmer choices with every crop transition and answers the question: 'should you consider this crop choice?' In addition, expert stakeholder consultations from the regions we selected allowed us to understand the riskiness of crop transitions; we accounted for factors like market risk and volatility, procurement systems and cultural factors in a qualitative assessment of risk based on these interviews.

In our model, if farmers choose crops that have an MSP, then we categorized that as a low-risk choice, and vice versa. Also, if at least 50% of the farmer's income comes from solar energy sale to the grid, we categorized that too as a low-risk choice. This is however debatable since stakeholder consultations have suggested that this might in fact be high risk, given that DISCOMs sometimes don't pay back the FiTs to the farmers on time.

These insights are backed by published studies that have attempted to understand how farmers perceive and adapt to or mitigate risks. For instance, Ali and Kapoor (2008) demonstrated through a survey of vegetable and fruit farmers in Uttar Pradesh, India, that of all the major sources of risk, farmers perceived price and production related risks as the most important source of risk to production. The study advocated for public intervention for better risk management, like the development of financial markets and promotion of market-based price and yield insurance schemes to safeguard the interests of farmers.

2.2.1 Farmer decision outcomes need to be aggregated to understand their impact on groundwater as a common pool resource

Once we have a sense of what choices farmers are likely to make, we can link them to groundwater models to understand the environmental implications of different policy scenarios. We can determine this by examining the trade-off between profitability and the water use intensity of a crop (Figure 7).

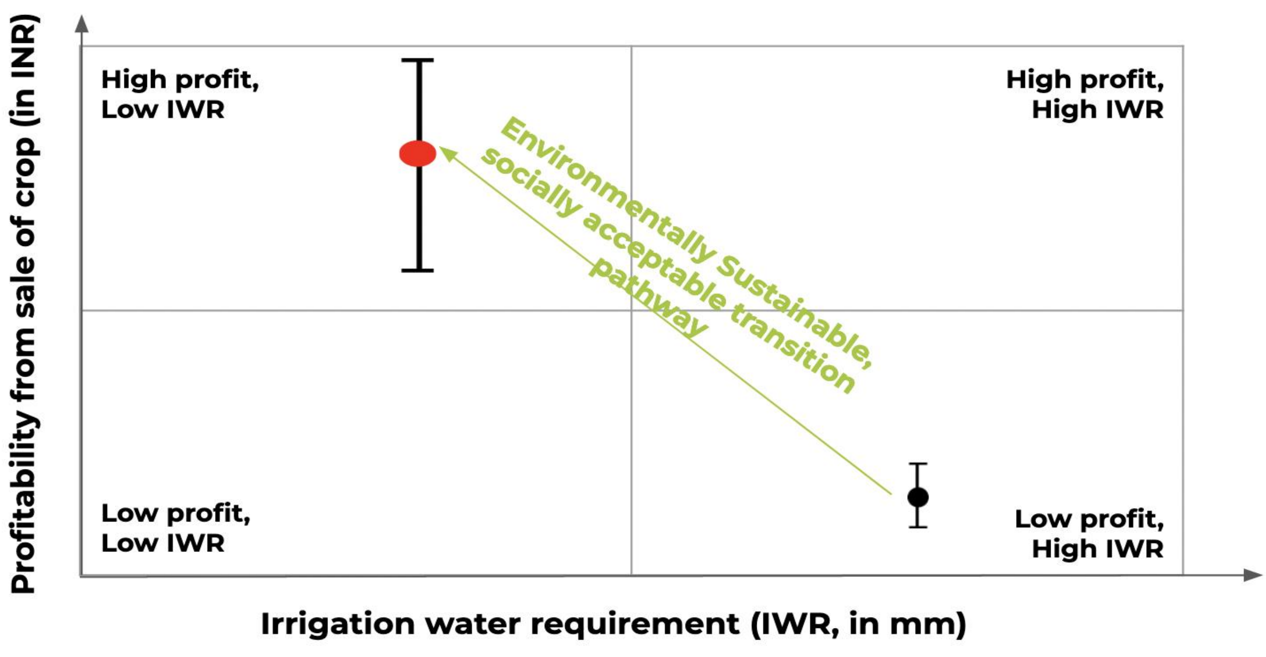

Figure 7. Irrigation profitability trade-off.

We define a sustainable transition as an event where an agent reduces water use while increasing income and either reducing or maintaining the same level of risk.

In this context, a 'sustainable transition that is also socially acceptable' would be one in which an agent transitions from a low profit-high water-low risk using crop to a high profit-low water using crop. The existence of sustainability transitions is promising, but they may not always eventualize because many factors including risk appetite, technical know-how, social networks and culture influence farmers' choice of crops.

This leads us to ask that if current likely transitions are not sustainable, what would it take to shift towards more sustainable transitions, i.e., crop choices that boost incomes and require less water.

2.3. Potential income, risk and design of solar irrigation scheme impact crop choice

Anticipating the impact of solar irrigation requires an understanding of how farmers will behave when solar irrigation is introduced. It is not reasonable to assume that farmers will continue to grow whatever they were before -- indeed the very intent of solar irrigation policies is to shift behavior. The key to understanding this is to recognize that solar irrigation may change the nature of the incentive for farmers -- specifically what constrains or motivates how much water a farmer pumps. When free electricity is made available to farmers, but only for a few hours a day, they are subject to rationing. The quantity of water a farmer may pump has an upper limit. A farmer would thus pump as much water as possible during the hours when electricity is available to maximize his/her income.

Although groundwater is technically free, it still has value to the farmer. In a farming context, the 'shadow price' (Box 1) is the value farmers ascribe to groundwater when they consider making a major capital investment (such as investing in a new borewell or switching to a plantation). We don't exactly know the farmers 'demand curve'; we can only infer it by observing farmer's choices.

BOX 1: In the absence of pricing, valuing groundwater via opportunity cost, shadow price and scarcity value

Opportunity cost: This refers to the opportunity of selling excess energy back to the grid through net metering and FiTs. Once farmers use as much water as they need to meet a crop's irrigation water requirement, they can either sell the energy back to the grid or pump more water.

Shadow price: This refers to the pricing mechanism used for pricing products and services that don't always have markets. In the case of water for agriculture, the shadow price of water reflects the value of crops that can be produced by the marginal unit of water consumed (Bierkens et al. 2019).

Scarcity value: This refers to the increased value of something when there is not much of it available. So, as groundwater gets depleted, it becomes more scarce and therefore more valuable. This value would manifest if groundwater licences were to be auctioned off to the highest bidder.

Regardless of the constraints and farmer choices, adoption of solar varies by state and policies.

In some of the scenarios in our modeling exercise, we believe that farmers will not adopt solar irrigation when income falls below current levels, as was the case in our case study in West Champaran, Bihar.

If farmers switch to solar irrigation but don't switch crops or area irrigated, only the mode of irrigation changes. There may still be climate benefits with no changes to groundwater at all.

2.4. Primary and secondary sources of data were used to develop the model

We made reasonable assumptions to arrive at:

- **Net Present Value (NPV):**

  Income from crops

  - Costs and revenues remain constant over a 25-year period. We also took average costs and revenues from multiple sources, especially for non-MSP crops.
  - NPV has been restricted to crop cultivation and does not include a farmer's other sources of income.
  - There are interstate variations in yield, costs and revenues. For instance, in some states, diesel is part of the cost of cultivation, but in others it is not. In our estimations, we accounted for these differences based on the source of energy for irrigation.
  - We assumed a discount rate of 10% which is the standard in NPV calculations for agricultural projects.
  - On the introduction of solar irrigation, agents receive a 30% subsidy from the central government and a 40% subsidy from the state government. This is currently the policy in most states, and we assumed this in our model.

  Income from solar electricity

  - With the introduction of solar irrigation, farmers have energy that they can use:
    - to pump groundwater to irrigate their fields; and/or
    - to sell the energy generated back to the grid.

    In some instances, i.e., in areas with active water markets, they could pump water from the ground to sell in these water markets as well. How much energy they use to pump and how much they sell back to the grid depends on the crops they are growing and their water requirement.

- We assumed a FiT of INR 5/kWh for all states included in this study. However, the sensitivity analysis (see annex) accounts for three FiTs: INR 3.5/kWh, INR 5/kWh and INR 7/kWh.

Water use (Irrigation Water Requirement - IWR)

- Crop water requirement for each crop was taken from multiple sources.
- To arrive at the IWR for each crop, we considered the different effective rainfall for each season. For instance, for the *kharif* season, we considered the effective rainfall for the months of June, July, August and September and for the *rabi* season October, November, December, January and February. In the rare cases where there is a third crop during *zaid* or the summer season, we took the effective rainfall for March, April and May.

Risk

- We made a qualitative assessment of risk as the farmer perceives it. There are two components to risk:
  - Price-related: for all MSP crops, we assumed that the price-related risk is low; for non-MSP crops we assumed it to be high. If a farmer is growing an MSP crop in one season and a non-MSP crop in another season, we categorized the price-related risk as medium.
  - Cultural: for farmers who continue to grow the crops they were always growing, we assumed that the cultural risk is low. However, for farmers who switch to any other crop, we assumed that the cultural risk is high.

Adoption of solar

- We did not assume that farmers will adopt solar across all scenarios. In cases where the after-transition NPV is less than the current NPV for multiple combinations of FiTs and subsidies, we assumed that farmers will not adopt solar because the cost of adoption is high.

Groundwater abstraction

- There are no assumptions around these estimations; the recharge and baseflow figures were taken from Central Ground Water Board reports, as cited in the case studies section.

- We also independently checked CGWB estimates of rainfall recharge and abstraction against our own estimates. Where there were discrepancies, these have been cited.
- Total groundwater abstraction in the district was estimated by multiplying the fraction of farmer agents following a particular cropping pattern by the total cropped area in the district.
- Groundwater abstraction and recharge (less baseflow) were then compared to derive the sustainability status before and after the introduction of solar irrigation.

3. CASE STUDIES TO UNDERSTAND AGENT TRANSITIONS

This section describes the six district-level case studies conducted in Bathinda (Punjab), West Champaran (Bihar), Bengaluru Rural (Karnataka), Anand and Botad (Gujarat) and Nadia (West Bengal) to understand constraints farmers face in different agrarian contexts. Our typology framework looked at availability of land, water and energy for irrigation. We picked two districts in each of the three typologies -- land constrained, energy constrained, and water constrained. A brief description of each district and how it fits into the land-energy-water constraints typology is provided in the annex.

Each case study begins with a description of the representative agents in the district, followed by a background on the land, energy and water constraints in the district.

First, we look at what constrains farmers in terms of access to land, energy and water. This was needed to understand whether irrigation pump solarization will induce sustainable transitions (where farmers move to less water-intensive crops that are also financially remunerative).

This is followed by the most probable transitions likely in these districts based on stakeholder consultations and their understanding of the larger ecosystem which the farmers in these districts consider while making crop, water and energy-related choices.

Next, we show the NPV, IWR estimations and risk assessments for all crop choices so that the trade-offs available to the farmers are clear.

We used these steps to predict likely farmer behavior. These were then aggregated by the extent of land under different cropping patterns to assess the probable implications for groundwater sustainability.

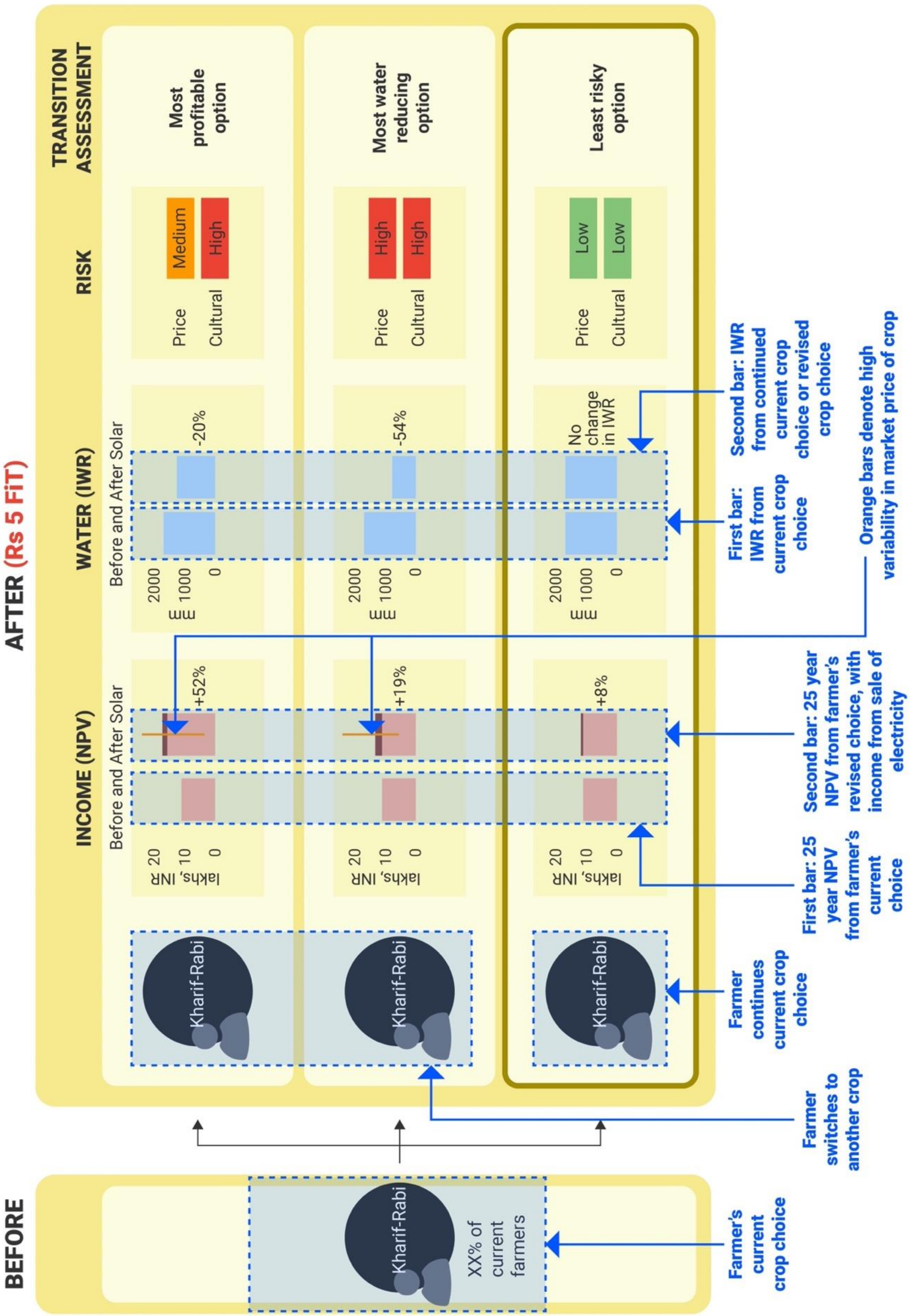

Figure 8 (a). Sample of a case study.

We believe that the most likely option is the risk minimizing one -- expert interviews suggested that farmers are risk minimizing rather than water conserving or profit maximizing. Each case study has one or two of these visualizations depicting the choices farmers are likely to make and the impact this is likely to have. This is illustrated in Figure 8 that needs to be read from left to right.

The first column represents the farmer's current crop choice during the *kharif* and *rabi* seasons. We arrived at this using district agricultural statistics. The top 2-3 representative farmers in each district were chosen.

The second column represents the sets of options available to farmers if they want to switch to other crops. These alternatives are based on current cropping patterns in the region, again based on district agricultural statistics. There are alternatives for option 1 and option 2, while option 3 is the scenario if the farmer continues growing the same crop as before.

The third column is the estimation of the farmer's NPV over a 25-year period. There are two bars. The bar on the left represents the farmer's NPV based on current crop choice; this bar will remain the same for all three options, since this represents the status quo. The bar on the right represents the farmer's NPV from either changing the crop choice or continuing with the same practice. The stacked bar in light pink represents income earned from crop cultivation and the dark brown bar represents income earned from sale of excess electricity to the grid. The orange lines on some of the bars denote variability in the market price of each crop. These have not been accurately estimated but show the difference between MSP and non-MSP crops.

The fourth column represents the IWR -- the bar on the left refers to the IWR for the current crop choice, while that on the right represents the IWR for an alternative or continued crop choice.

The fifth column is a qualitative estimation of a farmer's perception of price-related and cultural risks associated with switching to cultivating other crops. Price-related risks are higher for non-MSP crops that rely on market forces for price determination. Cultural risks are higher when farmers switch to growing new crops because it requires acquiring new skills, knowledge and expertise when compared to current practices.

The last column is an assessment of the choice based on farmer's income, water use and risk perception.

The dark brown border around the option at the bottom shows the most likely option based on our modeling exercise and stakeholder consultations with experts in these regions.

Figure 8(b) is a visual representation of the icons we have used to depict the different crops that are a part of the transitions.

Figure 8(b). Legend depicting icons of different crops that farmers can choose to cultivate in their respective districts.

Modeling offers many choices and combination of results depending on factors that we change. However, for the purpose of simplicity, we depicted our representation with fewer choices.

Also, this exercise is at a farm scale. To go from farm scale to district scale, we aggregated the choices of all the individual farmers in the district. We selected representative farmers in the region, restricted to 2-3 different crop choices, to understand if one farmer grows a particular crop, what the impact would be if more farmers were to grow this in the same region? What would the collective impact of all farmers' choices be on the region's groundwater sustainability (Figure 9)?

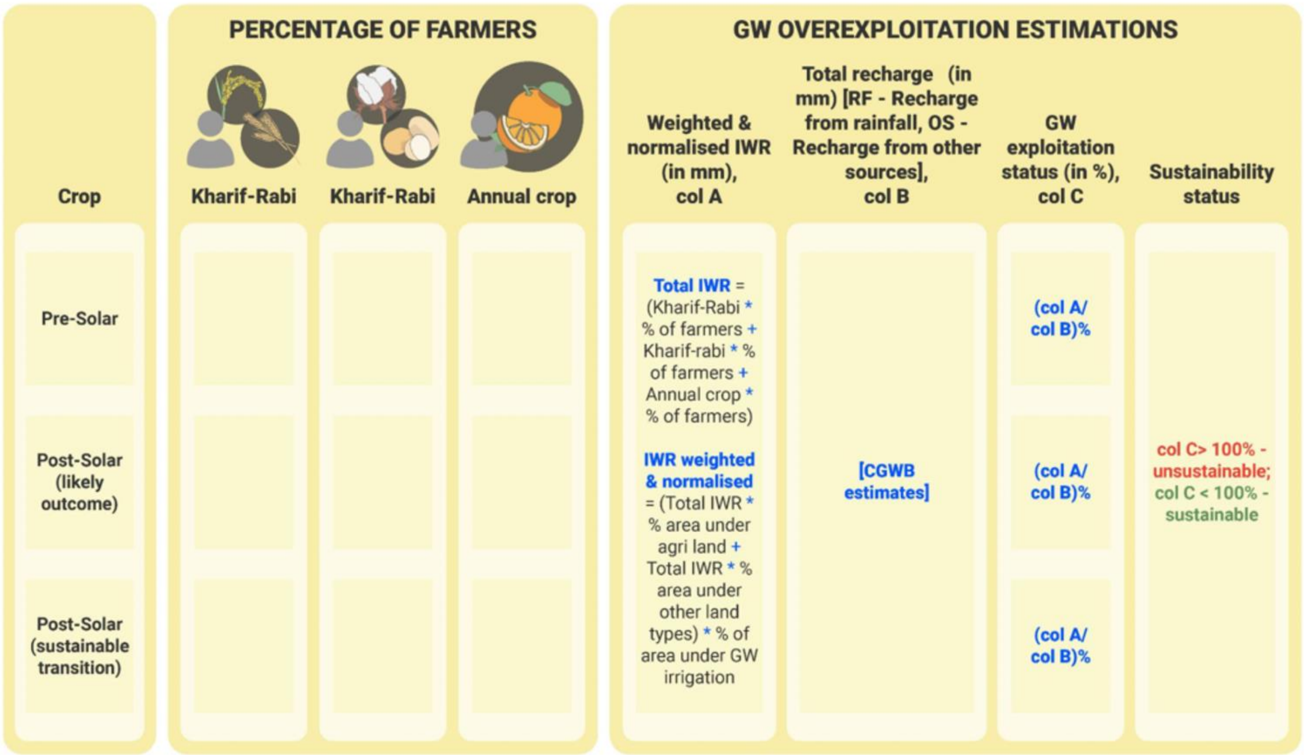

Figure 9. Sample visual depicting district wise groundwater overexploitation status for different combination of crops/choices.

The two sections in Figure 9 denote:

- **Percentage of farmers** - This refers to the percentage of farmers growing the most dominant crops in the district in focus. Each row adds up to 100%. Pre-solar percentage of farmers is based on current cropping patterns in the district. Post-solar (like outcome) distribution of farmers is based on the outcome of our modeling exercise and stakeholder discussions. Post-solar (sustainable transition) is a hypothetical distribution of farmers arrived at based on what distribution would be necessary for sustainable groundwater management in the district.
- **Groundwater overexploitation estimations** - Based on the cropping pattern in the district across multiple scenarios, we arrived at estimates for IWR, rainfall and used that to assess the groundwater status of the region. The formulas we have used are in figure 9.

Finally, we present the necessary conditions required in each of these districts for making choices that ensure groundwater sustainability and provide a summary of whether solar irrigation is suitable for that district or not.

We used the following datasets for each case study:

- 5th Minor Irrigation Census for the energy indicators - Source of energy, average hours of pumping per day and water indicator (distribution of tubewells, according to depth);
- Central Groundwater Board Classification - Aquifer type;
- Census of India 2011 and District Contingency Plans - Percentage of irrigated land;
- International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and District Contingency Plans - Agent profiles for districts, includes percentage of land under cultivation under each crop and percentage of crop irrigated versus rainfed, area under surface water irrigation and area irrigated by borewells;
- ICRISAT, Tamil Nadu Agricultural University (TNAU), Agrifarming, farmer.gov.in (for MSP crops), CEIC, Directorate of Economics and Statistics (DES), Department of Agriculture and Farmers Welfare, Ministry of Agriculture and Farmers Welfare, Government of India - Yield, cost of cultivation, price of crop sold estimates;
- Center for Study of Science, Technology and Policy (CSTEP) - Support with calculating energy estimates;
- Block wise ground water resource assessment 2020, Central Ground Water Board; and
- National Compilation on Dynamic Ground Water Resources of India, 2020, Central Ground Water Board.

We consulted the following experts to understand the most probable transitions in these districts.

Districts, State	**Experts Consulted**
Bathinda, Punjab	Dr. S.S. Kukal, Punjab Water Regulation & Development Authority
West Champaran, Bihar	Dr. Avinash Kishore, IFPRI-New Delhi, and Dr. Srivalli Krishnan, Bill & Melinda Gates Foundation
Bengaluru Rural, Karnataka	Dr. Veena Srinivasan, WELL Labs, and Mr. Manjunatha B, WELL Labs
Anand, Gujarat	Dr. Tushaar Shah, IWMI, and Mr. Mohammad Alam, IWMI
Botad, Gujarat	Dr. Tushaar Shah, IWMI, and Mr. Mohammad Alam, IWMI
Nadia, West Bengal	Dr. Aditi Mukherjee, IWMI, and Mr. Archisman Mitra, IWMI

3.1. Bathinda, Punjab: Introduction of solar irrigation with net metering and income from fits

In Bathinda, most farmers follow one of the following three cropping systems: rice-wheat (meaning rice in the *kharif* season, followed by wheat in the *rabi* season), cotton-potato and kinnow (a citrus fruit tree).[12] Among these crops, the rice-wheat cropping system requires the most water, followed by cotton-potato and then kinnow.

In this district, land is the major constraint, which means that there is no additional land available for irrigation. Almost 99% of cropland is already under irrigation, so there are no additional parcels available to expand irrigation to.

Farmers in Bathinda do not face an energy constraint. Currently, the Punjab government provides free or heavily subsidized electricity to farmers. Their shallow tubewells are powered by grid-connected electricity and on average, they receive 4-8 hours of electricity every day during the *kharif* and *rabi* seasons. This is comparable to the average of 4-5 hours[13] of electricity that solar panels provide, albeit with a little more certainty in timings.

As discussed earlier, groundwater in Punjab is held in massive alluvial aquifers; hence the pinch of groundwater decline has not yet been felt. Even in low rainfall years, there is no water scarcity. Studies have shown that the area under rice is completely disconnected from rainfall variability in Punjab (Fishman et al. 2011). Since 99% of the cultivable land in Bathinda is already irrigated and most farmers already practice irrigation-intensive rice-wheat cropping patterns, farmers can neither bring more parcels of land under irrigation nor increase their pumping. So, there is very little scope to further increase irrigation here.

In this situation, if solar irrigation were to be introduced in Bathinda, irrigation could either stay the same or decrease. The question is whether it could decrease enough to make a dent in the current rate of overexploitation. So, we ask: what crop choices are farmers likely to make? How will their profit change? How will the groundwater status change?

The ABM suggests that a 'sustainable transition' is theoretically possible**.**

It is possible for a farmer to move from growing rice-wheat or cotton-potato to kinnow; our calculations suggest that these transitions are both economically viable and less water intensive. They will earn more through sale of solar energy and crops; while significantly cutting down on their water use as kinnow's irrigation requirement is lower than that of rice-wheat and cotton-potato.

[12] The hyphenated crops refer to crops grown in the *kharif* and *rabi* seasons by the same farmer.
[13] That's in full capacity; some of the current models give power for 8-10 hours at varying capacities. For the purpose of this study we have taken a relatively conservative estimate.

But expert consultations suggest that this transition is unlikely to occur in practice**.**

We consulted water and agriculture experts to understand whether farmers would actually shift to less water-intensive crops. The interviews suggested that both rice-wheat and cotton-potato farmers are unlikely to budgse from their current cropping patterns at least in the medium term, even if solar irrigation results in a small increase in their earnings.

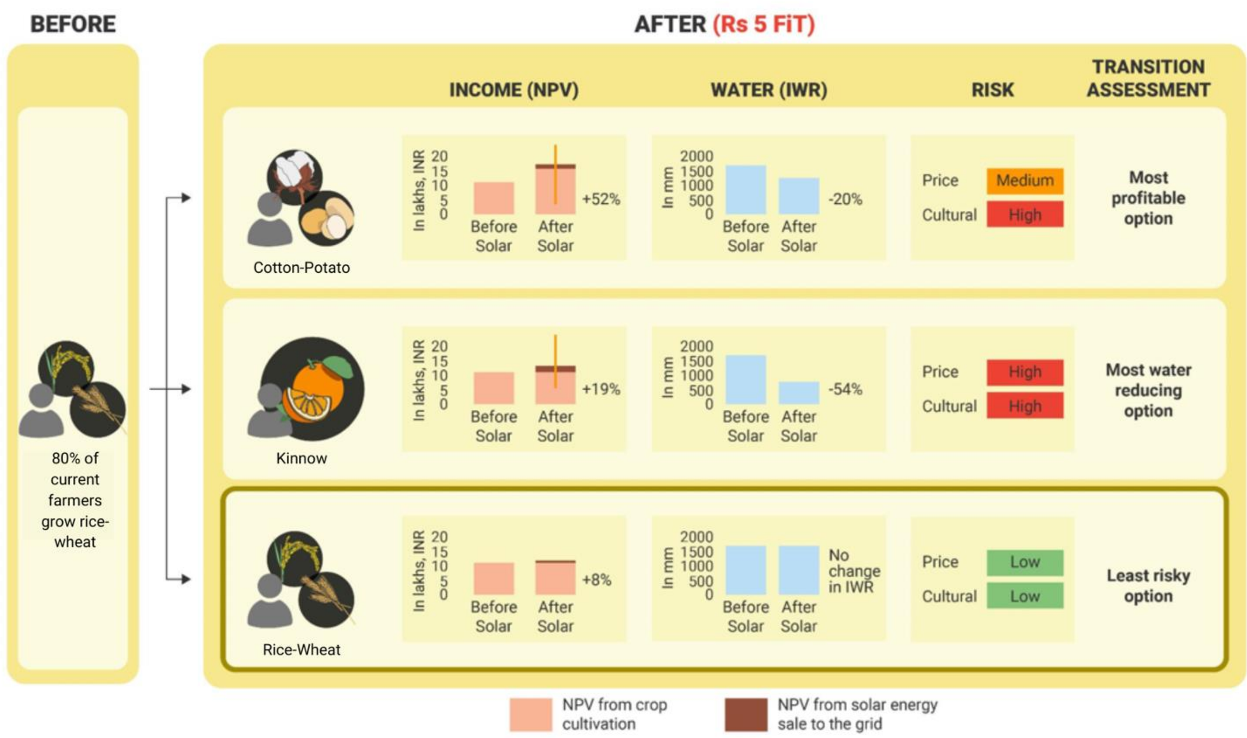

Figure 10. Options available to the rice-wheat farmer in Bhatinda, Punjab, and the choice most likely to be made.

Figure 10 presents the choices a rice-wheat farmer can make and is likely to make in Bathinda and the impact these choices will have on income (through NPV estimations) and water (irrigation water requirements). For the first representative agent farmer who grows rice-wheat, following are the three options available and the outcomes associated with each:

1) Switch to growing cotton-potato - From an income perspective, switching to cotton-potato is profitable and reduces water consumption marginally.
2) Switch to growing kinnow - This option reduces water consumption by a large amount but increases income marginally.
3) Continue growing rice-wheat - This keeps income at current levels, which is lower compared to other crop choices, but water consumption remains dangerously high.

Options 1 and 2 involve risk in two forms: 1) price-related risk, which crops without MSP are prone to since they are subject to market forces, and 2) cultural risks, where farmers are hesitant to move away from growing crops that they are familiar with.

Hence, it is likely that the agent farmer will continue growing rice-wheat. Solar irrigation might only marginally increase the profit, owing to the initial capital cost. This choice is likely to result in continued overabstraction of groundwater resources, as there is no change in irrigation water requirement. In subsequent sections we describe why these choices are 'locked-in' despite clear advantages associated with changing crop choice.

Our sensitivity analysis (see annex) showed that at low FiTs and low subsidies, it is not profitable for a rice-wheat farmer to continue growing the same with solar irrigation. In other words, adoption of solar irrigation itself is likely to be low if farmers remain risk averse. Only when the FiT crosses a threshold of INR 5/kWh and a subsidy of 70% is it profitable for the farmer to grow rice-wheat after switching to solar. At this FiT, decarbonization of agriculture (climate benefits) may occur but without any implications on groundwater.

However, it is important to note that switching to cotton-potato and kinnow is profitable for the farmer across most FiTs and subsidies. But earlier descriptions of the farmer's perceptions of risk show that this is a highly unlikely outcome.

The second most dominant farmer in the region – growing cotton-potato - has three options.

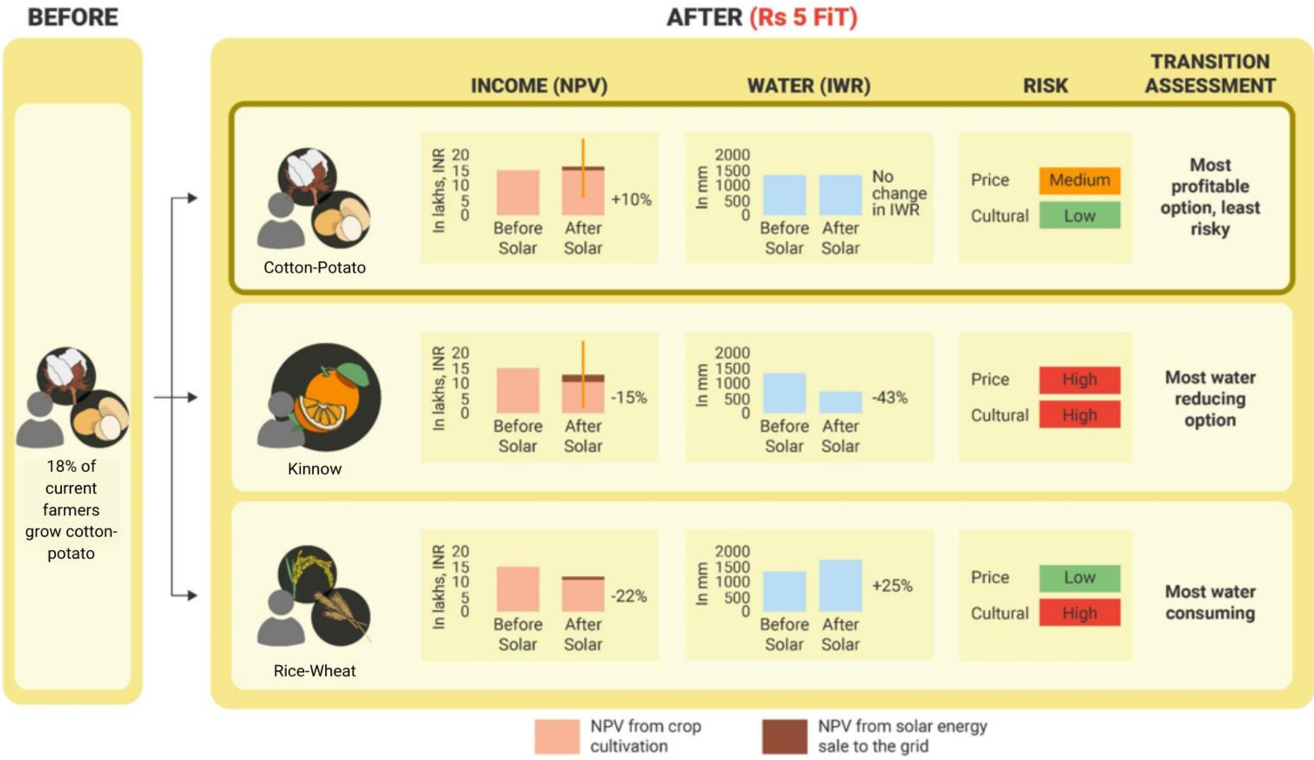

Figure 11. Options available to the cotton-potato farmer in Bhatinda, Punjab, and the choice most likely to be made.

Even in this case, the farmer is unlikely to switch out of growing cotton-potato. This agent farmer will earn a small additional income from the sale of excess energy to the grid.

Figure 11 clearly shows that continuing to grow cotton-potato is profitable and keeps water consumption at the same level. Switching to kinnow decreases income marginally, while reducing water consumption by a large amount. However, switching to rice-wheat decreases income and is likely to increase water consumption. This is an unlikely transition. Once farmers have accepted the higher risk involved, they are unlikely to switch back. Hence, sticking to cotton-wheat is the most likely option for the farmer.

Our sensitivity analysis for the cotton-potato farmer (see annex) reveals that solar irrigation as an option is only profitable at a starting FiT of INR 3.5/kWh and subsidy of 50%. Switching to any other crop is just not financially remunerative for this farmer.

Given that the farmers are unlikely to change their behavior for profits, the only way forward is to reduce the risks they face.

There are two reasons why farmers in Bathinda are likely to continue growing the crops they already do, even with the introduction of solar irrigation:

- Rice, wheat and cotton are all sold at state-run APMCs, which means the government provides guaranteed MSPs and the Food Corporation of India (FCI) procures their produce, insulating these farmers from wild price fluctuations.
- Farmers are ‘locked-in’ the practice of growing crops they have been cultivating for generations and resist changing this behavior. Lock-ins in agriculture exist all across the country and are evident across our other case studies as well.

Bathinda could be representative of other districts in Punjab. Many things need to change to enable diversification to less water-consuming crops. Since farmers are locked into the practice of growing a water-intensive combination of rice-wheat, the entire ecosystem for agriculture in places in Punjab is set up to grow rice-wheat. To truly shift to other crops, all the stakeholders and incentives should align to enable this sustainable transition.

When individual agent/farmer decision are added up, at the district level, the status quo result is groundwater overabstraction. This is already the case in large parts of Punjab and validates the CGWB’s groundwater overexploitation status for the district -- where six out of nine blocks in the district are ‘overexploited’. Figure 12 shows the different combinations of crops and the GW overexploitation status associated with them. For a truly sustainable transition to occur, a substantial number of farmers must move away from cultivating rice-wheat to kinnow or other less water-intensive crops.

Even kinnow, which is less water-intensive than rice-wheat or cotton-potato, requires more water than is currently available through recharge (from multiple sources in the district), indicating a clear need to look at other crops, like horticultural crops or possibly even millets, that will allow farmers in this region to collectively stay within their water budget. Even if the groundwater overexploitation status is high with kinnow, it is comparatively less than growing rice-wheat and is a good starting point for reducing groundwater abstraction in the region.

	PERCENTAGE OF FARMERS			GW OVEREXPLOITATION ESTIMATIONS			
Crop	Rice-Wheat	Cotton-Potato	Kinnow	Weighted & normalised IWR (in mm)	Total recharge (in mm) [RF - Recharge from rainfall, OS - Recharge from other sources]	GW exploitation status (in %)	Sustainability status
BEFORE	80%	18%	2%	870		228%	Unsustainable
AFTER (likely outcome)	80%	18%	2%	870	RF - 67 OS - 314 Total - 381	228%	Unsustainable
AFTER (sustainable transition)	0%	0%	100%	417		110%	Comparatively more sustainable

Figure 12. Collective impact of individual agent decisions on Bathinda's groundwater abstraction status.

The IWR estimation is made accounting for crops that are grown in the district, fallow land in the district, and then excluding the area under surface water irrigation.

The groundwater overexploitation status that we estimated here aligns with the CGWB's classification of groundwater status in six out of nine blocks as 'overexploited', and one each being 'critical', 'semi-critical' and 'safe'.

Some key factors that need to be considered to induce sustainable transitions with solar irrigation in this region include:

- ***Strong market linkages to break the lock-in***: Setting up strong market linkages for other horticultural crops could incentivize this shift. This would include setting up cold storage infrastructure and connecting farmers with buyers – both of which are necessary to ensure that farmers can sell their produce at a fair price in the market.
- ***Improving messaging for behavior change***: Communicating the importance of growing crops within the region's water budgets is critical. In the 2022 state budget, the Punjab government announced incentives to the tune of INR 4.5 billion for farmers who can switch from conventional methods of rice cultivation to alternative and less water consuming direct rice seeding methods, and consequently save

groundwater by 20% (Prakash 2022). It remains to be seen if such incentives will translate into behavior change on the ground.

- ***Move from rationing to pricing structures***: Farmers in Punjab currently receive free or subsidized electricity. It is rationed only in terms of the number of hours of supply. By moving to solutions like solar irrigation, governments could use 'pricing' as a 'stick' to change behavior around crop choice and water consumption. However, this policy choice is sensitive and likely to be unpopular; no policymaker is going to commit to pricing even though rationing (or rather overgenerous allocation well above the sustainable limit) can have severe long-term implications on the region's water table.

  This change in policy must be accompanied by other supportive mechanisms that assure farmers that their incomes would not be impacted as a result of shifting to less water-intensive crops. In fact, even in the 2022 budget, the government allocated INR 6.9 billion of its annual budget towards providing free power to agricultural tubewells in the state (Prakash 2022). This is almost 60-65% of the total budgetary allocation to the agricultural sector in the state. It remains to be seen which incentive is stronger -- free power or alternative direct rice seeding methods.

Different contexts with different challenges will require different solutions. In the case of Bathinda, solar irrigation may not be the right solution given the free electricity regime, deep lock-ins and lack of assured MSPs for more sustainable crops. As our analysis found, its introduction is unlikely to prompt farmers to shift. We need to conduct additional modeling exercises to pick a solution that is best suited to the context and can effectively encourage farmers to diversify and prioritize more water-prudent practices.

One possibility to use solarization to induce sustainable transitions is to ensure that an income guarantee from solar sales is equivalent to what the MSP currently provides. For income from sale of solar energy alone to compensate for loss from sale of crops, the FiT has to be as high as INR 27-28/kWh. With an even higher FiT, farmers could potentially be nudged to reduce the area under rice-wheat. It is also important to note that it is highly likely that the DISCOM may not accept as high a FiT as the hypothetical one suggested here. Stakeholder consultations have suggested that DISCOMs find even the current FiT too high. Hence, this may not be a real possibility on the ground.[14]

[14] Evaluating the appropriate FiT to balance out farmer and DISCOM interests is beyond the scope of this work.

3.2. West Champaran, Bihar: Introduction of solar irrigation without net metering and no income from fits

In West Champaran in Bihar, most farmers grow rice-wheat or sugarcane,[15] which both require a lot of water. We found that energy is a constraint, while land and water are not.

While most of Bihar is fully electrified[16], farmers in some parts of the state, like West Champaran, still rely on diesel pump sets for irrigation. The electricity connections are mostly for households. Unlike the Bathinda case study, energy comes at a cost here, and adds to the cost of production.

Depending on the crop, the cost of irrigation could be anywhere between 10-20% of the total cost of production. This case study assumed that solar irrigation systems are not connected to the grid, hence farmers here will be unable to benefit from FiTs. There is no land constraint here; almost 70% of the total land area is under irrigation with irrigation-intensive rice-wheat cropping patterns. This means that farmers can bring more parcels of land under irrigation.

Water is not a constraint because groundwater in Bihar is held by alluvial aquifers and farmers in this region do not yet feel the pinch of groundwater decline. Even in low rainfall years, they don't face a water challenge. There are two reasons for this. Firstly, the average annual rainfall is high in Bihar (around 1,200-1,300 mm). Secondly, farmers in Bihar have not been able to exploit groundwater resources because of lack of access to grid-connected electricity. This means the aquifers in Bihar are still productive.

In this situation, if we were to introduce solar irrigation in West Champaran, what crop choices are farmers likely to make; how will their income change and how will the groundwater status change?

The agent-based model suggests a 'sustainable transition' is theoretically possible. This means that farmers could potentially move to growing maize-potatoes that have lower irrigation water requirements compared to rice-wheat.

[15] The hyphenated crops refer to those grown in the *kharif* and *rabi* seasons by the same farmer.

[16] It is important to note here that full electrification as per government programs only refers to electrification of households and does not extend to agriculture. Reviewer comments have suggested that in places like Bihar, households are often quite far away from the fields and electrification of households doesn't automatically mean that they now have access to grid-connected electricity for their borewells. Sharma (2018) writes about 100% electrification of most parts of Bihar as of 2018 while The Hindu Businessline (2021) suggests that they may not be fully accurate. Hence this case study took into account farmers using diesel pump sets to irrigate their fields.

We consulted with water and agriculture experts to understand whether farmers would shift to less water-intensive crops, based on our model (Figure 13).

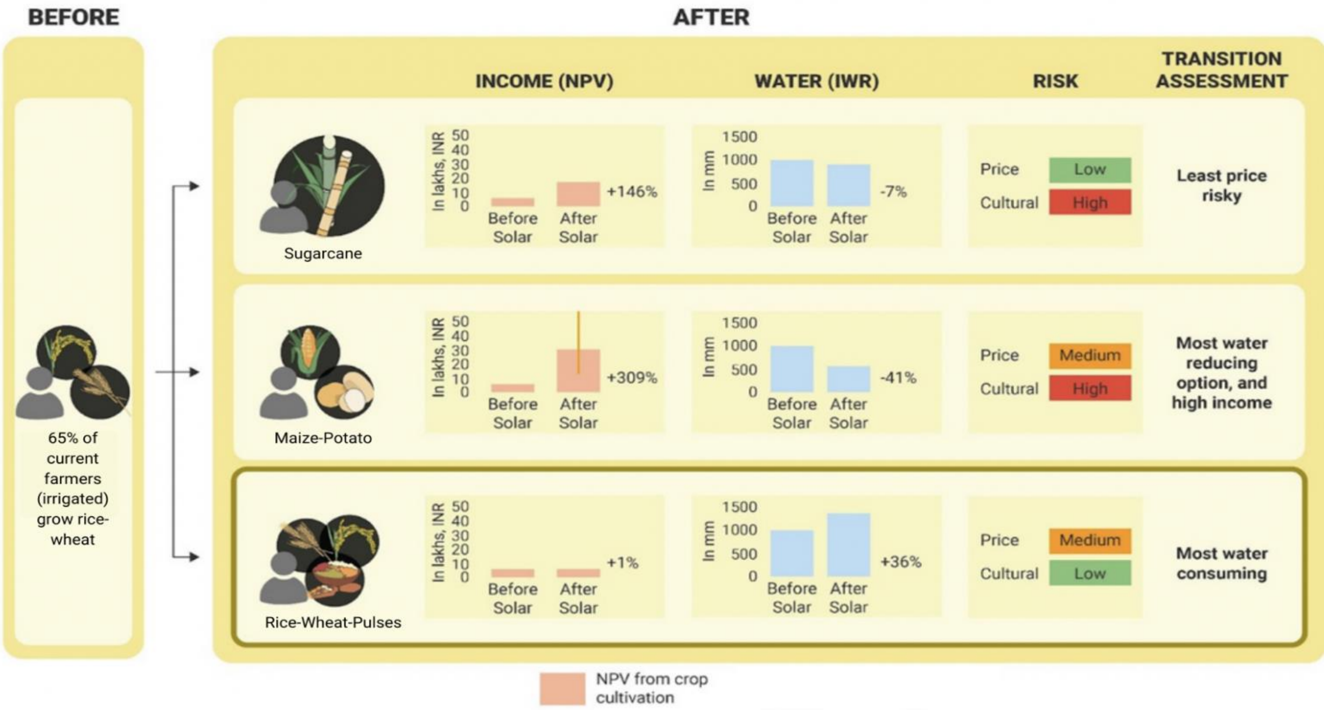

Figure 13. Options available to the rice-wheat farmer, and the choice most likely to be made.

The figure shows that the rice-wheat farmer is most likely to continue growing rice-wheat, but also incorporate a third summer crop, most likely minor pulses.

The choice made aligns with the income-water-risk framework we have proposed.

While income from sale of sugarcane is higher than that from rice-wheat and minor pulses, it is still unlikely to be the most dominant choice of most farmers because of broken procurement systems for sugarcane. Newspaper articles have suggested that sugarcane procurement in parts of Bihar is plagued by middlemen who buy the sugarcane at very low prices. Hence, there is an element of risk, which is why switching to sugarcane will not be an obvious choice for most farmers. Farmers, especially those who haven't traditionally been growing sugarcane, are likely to view this as risky.

For maize-potatoes, the income is high, but is also highly variable since potatoes are subject to market forces. So even though this is the least water consuming option, it is also an unlikely transition for rice-wheat farmers since they might view it as being risky.

With solar irrigation, rice-wheat farmers in West Champaran will benefit in three ways:

- ***It will reduce the cost of irrigation*** by replacing diesel with solar-powered pump sets. However, there is no option for net metering in this case. Diesel pump sets are not connected to the grid, so these solar powered irrigation pump sets are likely to be standalone units. Farmers will not have a second stream of income through net metering, which is why the increase in income from the inclusion of a third crop is only marginal.
- ***It will allow them to sow the kharif crop on time.*** Delayed monsoons typically delay the sowing of crops. Diesel is expensive and mostly used only during the dry *rabi* and *zaid* seasons. Hence, for the *kharif* season, farmers try to wait for the monsoon to sow their seeds.
- ***It will allow them to grow a third summer crop***, most likely minor pulses or green vegetables. Growing a third crop allows farmers to diversify their income sources and mitigate crop losses across seasons. Also, this third summer crop is comparatively less water-intensive compared to rice-wheat.

We also focused on sugarcane farmers in the region as our second agent in West Champaran. Figure 14 shows that sugarcane farmers are likely to continue growing the crop.

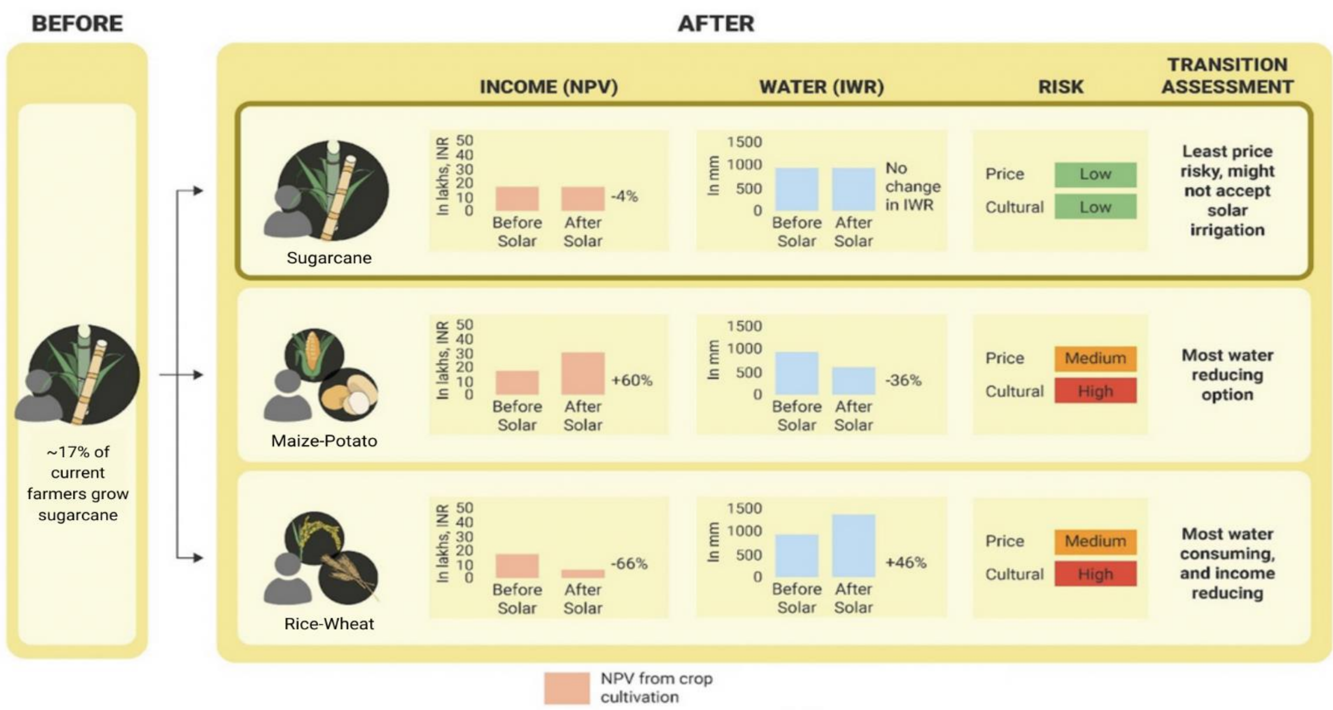

Figure 14. Options available to the sugarcane farmer, and the choice most likely to be made .

There is a strong sugarcane industry (ethanol production) in West Champaran, which means there is demand for the crop. If this industry continues to grow, it is likely that these farmers will continue growing the crop to meet this demand. However, the farmers are unlikely to take up solar irrigation since it results in a marginal decline in income.

In the case of West Champaran, which could possibly be representative of other districts in Bihar, there may not be a need to make a drastic shift from rice-wheat to less water-intensive crops because the water tables in Bihar are not as imperiled as in Punjab. Moreover, farmers will financially benefit from the introduction of solar irrigation (as they can shift from expensive diesel-powered pumps).

When each of the individual agent/farmer decisions are added up, at the district level, the status quo is likely to result in high groundwater over abstraction. For a truly sustainable transition in Bihar, a substantial number of farmers must move away from cultivating rice-wheat and sugarcane to crops like maize-potato. However, groundwater depletion is less of a problem in Bihar as recharge is high in most parts of the state. Also, Bihar has traditionally had much less access to groundwater owing to a lack of access to electricity. Hence, they still have a lot of groundwater left to tap for agriculture.

	PERCENTAGE OF FARMERS				GW OVEREXPLOITATION ESTIMATIONS			
Crop	Rice-Wheat	Rice-Wheat-Minor Pulses	Sugarcane	Maize-Potato	Weighted & normalised IWR (in mm)	Total recharge (in mm) [RF - Recharge from rainfall, OS - Recharge from other sources]	GW exploitation status (in %)	Sustainability status
BEFORE	65%	0%	20%	15%	316		91%	Sustainable
AFTER (likely outcome)	65%	0%	20%	15%	396	RF - 196 OS - 150 Total - 346	114%	Sustainable
AFTER (sustainable transition)	0%	30%	10%	50%	230		66%	More sustainable

Figure 15. Collective impact of individual agent decisions on West Champaran's groundwater abstraction status.

The groundwater overexploitation status estimation we arrived at (Figure 15) aligns well with the CGWB block wise classification where all 18 blocks in the district are in the 'safe' category.

Solar irrigation may be the right solution for this district. It will reduce the cost of irrigation, while simultaneously boosting incomes in this state, all of this while ensuring groundwater sustainability. If introduced with an appropriate FiT, there is likely to be better uptake of solar irrigation in the state.

3.3. Bengaluru Rural, Karnataka: Introduction of solar irrigation with net metering and income from FiTs

In Bengaluru Rural, Karnataka, a majority of the farmers are rainfed. Most of these farmers grow finger millet or minor pulses, along with a few fruit trees like mango or tamarind; none of these are water intensive. The remaining farmers, i.e., those with access to borewells, grow arecanut (a crop that grows year-round and is water intensive) or vegetables like carrot along with maize.

In Bengaluru Rural, we found that it was water that stood out as the major constraint. There are no constraints around land and energy availability.

Bengaluru Rural relies on a hard rock aquifer, much like an egg carton, meaning they are fast responding and local. During rain-deficit years, they quickly run out of water, and during rain-surplus years, they fill up equally quickly. Most hard rock regions in peninsular India tend to behave like egg cartons, which is why water tends to be a constraint in these regions as availability depends on the monsoon.

Land and energy are not major challenges. Only 20% of the total land area is irrigated, which means that there is still scope for farmers to bring additional parcels of land under irrigation. In terms of energy, farmers who irrigate have access to deep borewells (often as deep as 3048-3657.6 meters (m) and receive around 4-8 hours of electricity every day.

In this situation, if we were to introduce solar irrigation in Bengaluru Rural, what crop choices are farmers likely to make; how will their income change and how will the groundwater depletion status change?

Similar to the previous two case studies, a sustainable transition is possible here as well. If farmers continue to grow finger millet in large numbers, it is likely to have a low irrigation water requirement and thus leave a smaller water footprint. However, farmers growing finger millet in Bengaluru Rural in Karnataka earn much less than rice-wheat farmers because of the former's low productivity compared to rice-wheat. So, it is important to find a balance between improving farmer's income and maintaining low irrigation water requirement.

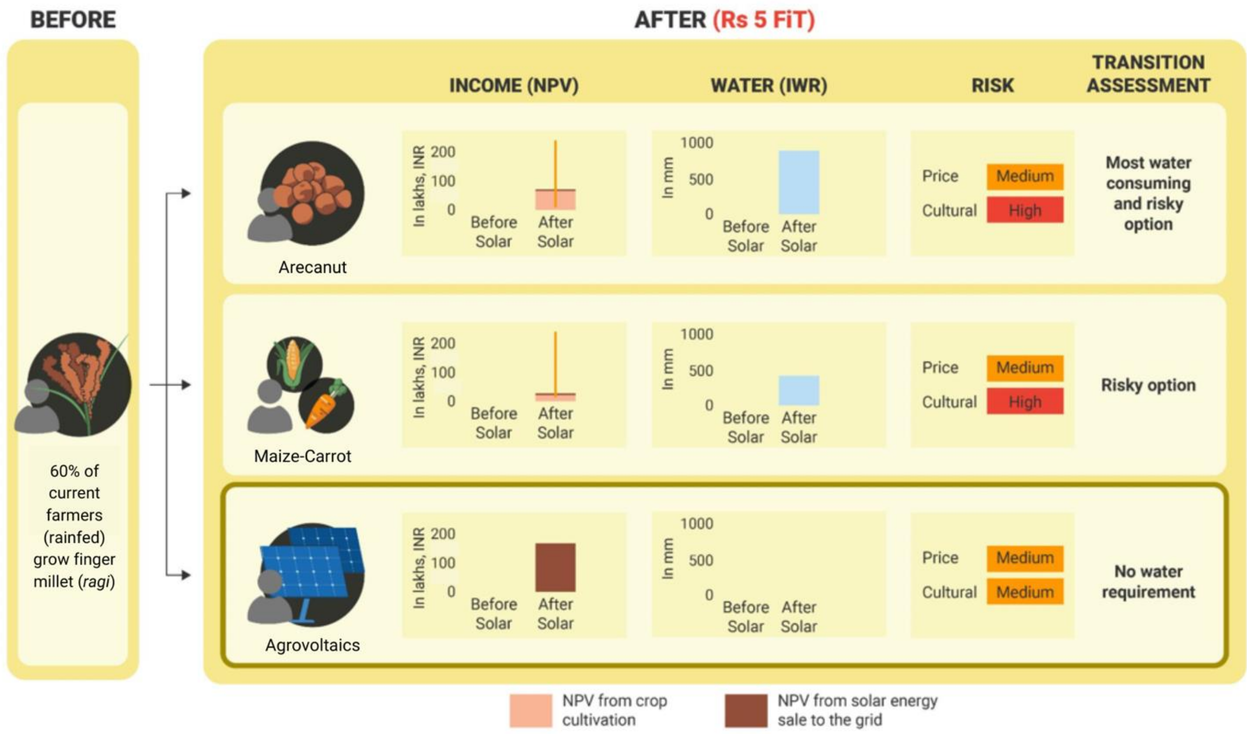

Figure 16. Options available to the finger millet farmer, and the choice most likely to be made.
Note: Unlike other transitions, in this case we did not add percentages to enable comparison between pre- and post-irrigation outcomes for the farmers because the baseline (finger millet's NPV and IWR estimates) are very low.

In the first case (Figure 16), we focused on finger millet farmers[17]. It is unlikely that they will add a borewell to their farms if they get access to solar-powered pumps; the cost of setting up a borewell in hard rock aquifer regions in Karnataka is high (~between INR 4.5 lakhs to 5 lakhs), especially where the depth to groundwater is high (around 1,00 0 - 1,500 meters below ground level (mbgl). Farmers may not willingly want to bear this additional cost burden. In any case, from a policy perspective it would be important to dissuade farmers from adding more borewells in a region with hard rock aquifers, because of increasing groundwater depletion.

The sustainable pathway here for a finger millet farmer would be to switch to agrivoltaics. Agrivoltaics refers to the co-location and use of land for both crop cultivation and solar energy generation. However, the initial capital cost of setting up agrivoltaics can be quite expensive, running into million Rupees, despite central and state government subsidies. If additional financing mechanisms can be explored for covering this initial capital cost, this

[17] In figure 17, the pre-solar NPV i.e., the NPV of the finger millet farmer is around INR 53,333 over 25 years. Given the scale of the y-axis, it looks almost like zero in the graphs.

option may prove to be remunerative and sustainable. It is also important to note that agrivoltaics typically involve the cultivation of certain shade crops, i.e., crops whose productivity won't be significantly impacted if grown in the shade of the PV modules. While we have taken finger millet as the crop in this case study, additional research needs to be done to identify a more suitable shade crop for this particular district. Crop choice for agrivoltaics varies from region to region.

For the second agent, we chose to focus on farmers who grow the more water-intensive arecanut (Figure 17).

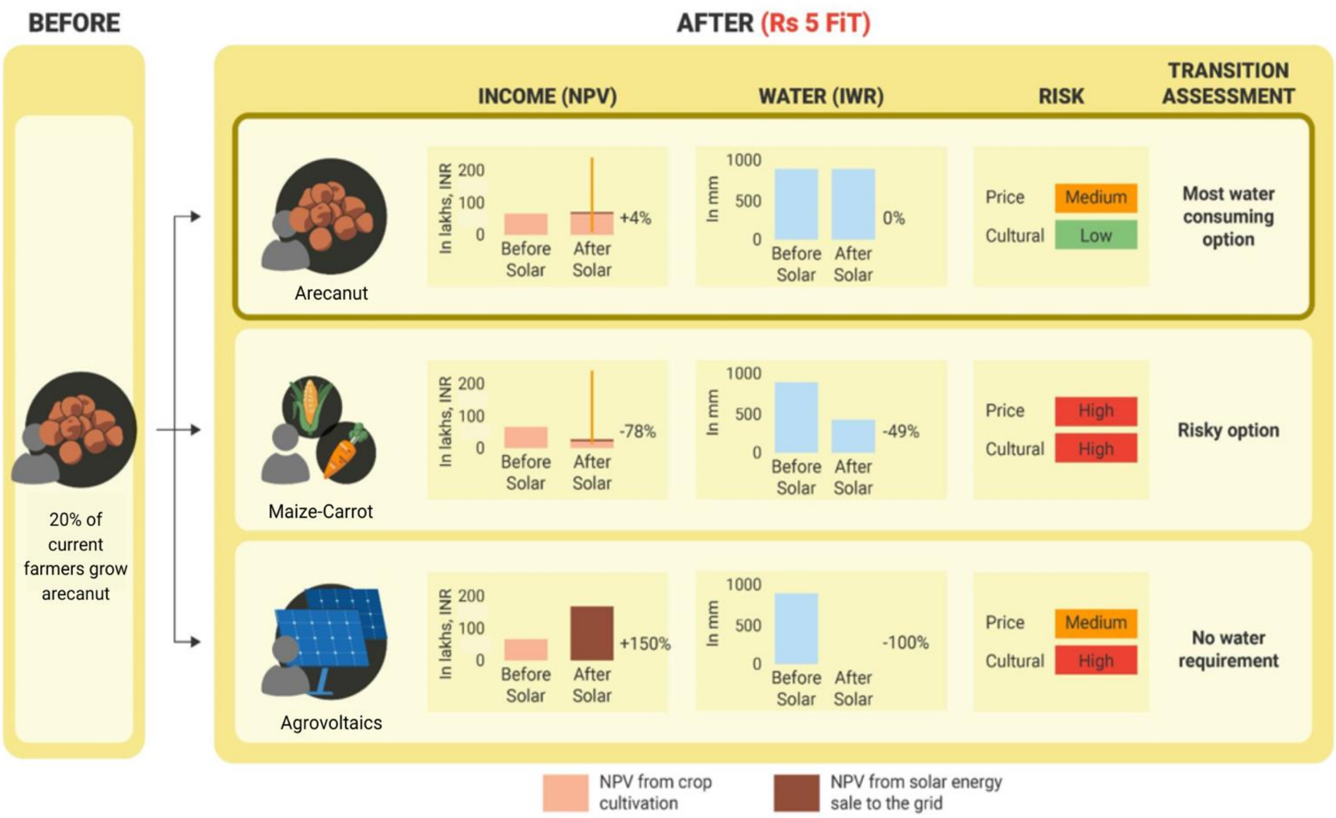

Figure 17. Options available to the arecanut farmer, and the choice most likely to be made.

Arecanut farmers are unlikely to switch out of growing this crop in the near future because it is one of the highest-priced cash crops in the region. Based on fieldwork we conducted in the region over the last two years, farmers who were growing minor pulses and groundnut previously have been borrowing credit and leasing additional parcels of land to grow arecanut. It has an assured market price since private buyers have created linkages for buying and trading them to manufacture *supari* (betel nut). Institutions like the Central Arecanut and Cocoa Marketing and Processing Co-operative (CAMPCO) have been responsible for strengthening market linkages for crops like arecanut.

Here, the arecanut farmer has taken a profitable option. We define this as medium risk only because market prices are likely to fluctuate for all non-MSP crops. However, in this case, the existence of a flourishing *gutka/supari* industry and strong procurement systems has de-risked these farmers with a steady demand for arecanut.

In Bengaluru Rural, solar irrigation, in the form of agrivoltaics, could be a possible path for finger millet farmers in the region, ensuring water positivity and carbon positivity. Two models of agrivoltaics are being piloted across the country:

- Leasing model - where a private company leases the plot of land from a farmer and pays the farmer a monthly lease for harvesting solar energy and selling it back to the grid; and
- Own-cost model - where farmers instal solar panels from their own pocket or with government subsidies and sell the excess energy back to the grid. In this model, farmers will typically have to grow exotic vegetables with high market price to offset some of the capital cost of setting up PV modules. Finger millet may not be a feasible option in this case.

In addition, to ensure that marginal and small farmers also benefit from solar irrigation and prevent dispossession, Farmer Producer Organisations (FPOs)/companies could be a path towards mass solarization (Aggarwal and Chandramouli 2022). Farmers' collectives could achieve economies of scale by bringing together a group of farmers in a village and selling the excess energy collectively back to the village or the local DISCOM.[18] It is possible that arecanut farmers may also be nudged to move to agrivoltaics, if they see that net metering is benefiting farmers financially, and there is trust between the DISCOM and the farmer.

When each of the individual agent/farmer decisions are added up, at the district level, the continuation of current cropping practices is likely to result in high groundwater over abstraction. This is already the case in some parts of Bengaluru Rural district. For a truly sustainable transition to occur, a substantial number of farmers must move away from cultivating arecanut to agrivoltaics or photovoltaics. This is the only transition that is likely to increase farmers' incomes, while ensuring that the water resources in the district are managed sustainably (Figure 18).

[18] There is an inherent limit at the village scale on how much agricultural lands can be converted to solar plants. The maximum capacity of solar energy that can be integrated at the village level distribution grid is usually 1-5 MW. That is on a maximum of 10 ha, which could mean about 10-15 marginal farmers.

	PERCENTAGE OF FARMERS				GW OVEREXPLOITATION ESTIMATIONS			
Crop	Ragi	Arecanut	Maize-Carrot	Agrivoltaics	Weighted & normalised IWR (in mm)	Total recharge (in mm) [RF - Recharge from rainfall, OS - Recharge from other sources]	GW exploitation status (in %)	Sustainability status
BEFORE	60%	20%	20%	-	87		272%	Unsustainable
AFTER (likely outcome)	30%	20%	20%	30%	87	RF - 21 OS - 11 Total - 32	272%	Unsustainable
AFTER (sustainable transition)	30%	10%	20%	40%	59		185%	Comparatively more sustainable

Figure 18. Collective impact of individual agent decisions on Bengaluru Rural's groundwater abstraction status.

Currently, CGWB has classified all four blocks in the district as 'overexploited,' which aligns with our own estimations. One thing to note here is that some district contingency plans for Bengaluru Rural have shown the cultivation of rice and sugarcane as well, which has not been included in the crop profile for this report. Including it would further worsen the sustainability status of the district.

Solar irrigation, particularly in the form of agrivoltaics, may be the right solution for this district. It will provide opportunities for boosting farmer incomes while simultaneously ensuring that groundwater resources are managed sustainably. This is particularly important in water-stressed regions like Bengaluru Rural and could work well if the capital cost of financing associated with setting up agrivoltaics can be managed well.

However, it is also important to keep in mind that most of our understanding of agrivoltaics is based on pilot projects on a small scale; hence we do not recommend large-scale conversion of agricultural lands into agrivoltaics. The example above is for purely illustrative purposes on what is required to reduce this region's water stress. In fact, in some arid parts of the region, apart from agrivoltaics, agroforestry -- with and without carbon financing -- is also being piloted. Similar to agrivoltaics, even agroforestry is believed to bring both economic benefits for farmers and environmental benefits to the region in the form of carbon sequestration.

3.4. Anand, Gujarat: Introduction of solar irrigation with net metering and income from FiTs

In Anand, most farmers grow rice-wheat, tobacco-potato and banana.[19] Among these crops, it is rice-wheat that requires a lot of water, while tobacco-potato and banana do not. We found that Anand is slightly land constrained, with no water or energy constraints.

Almost 80% of the arable land in Anand is irrigated, primarily through canals. This is because farmers here have access to grid-connected electricity, and they have shallow tubewells to pump water for 4-8 hours every day.

In terms of water, most of the district is underlain by coastal alluvial aquifers, which means that they behave like bathtubs. In this district, each individual farmer's pumping has a relatively small impact on the water table, as water moves quickly across the aquifer system. The average annual rainfall in this district is around 800 mm, which is marginally below the national average.

In this situation, if we were to introduce solar irrigation in Anand, what crop choices are farmers likely to make; how will their income change and how will the groundwater depletion status change?

The ABM suggests a 'sustainable transition' is theoretically possible, which means that farmers could potentially steer away from a rice-wheat cycle to less water-consuming crops.

We consulted with water and agriculture experts to understand whether farmers would shift to less water-intensive crops, based on our model. They suggest that this transition is unlikely to occur in practice.

Farmers in Anand are in a unique position. Apart from selling excess energy back to the grid, they could also sell water, because the wells are productive**.** Anand has active water markets, where farmers use tubewells to extract water and sell to their neighbors. For every hour of tubewell usage, farmers typically charge anywhere between INR 70 and INR 100.

There is anecdotal evidence to suggest that the water markets in Anand have been hardening[20], with steadily increasing water prices, as a response to the availability of net metering. What this means is that since there is an opportunity cost involved now, farmers can either sell the energy or the water, and the price of water has risen to compete with

[19] The hyphenated crops refer to crops grown in the *kharif* and *rabi* seasons by the same farmer.
[20] Hardening often refers to market conditions when prices are rising steadily and slowly, and there is not much market volatility.

the price of energy. This means that income could potentially come from three streams - the sale of crops, water or energy.

We found that rice-wheat, banana and tobacco-potato farmers are unlikely to transition to more water-sustainable crops. This is because the dairy industry in Anand drives all crop choices in the district. The dairy cooperative, the Gujarat Cooperative Milk Marketing Federation Limited or Anand Milk Producers Union Limited, more popularly known as Amul, is based out of Anand. The dairy cooperative is the largest in Asia. Thousands of small and medium farmers in the district are a part of this cooperative and have been able to significantly improve their incomes through the cooperative. Given how profitable the dairy industry is, farmer crop choices are highly influenced by demand from this industry. Stakeholder consultations have suggested that the livestock owners in Anand completely absorb/buy the crop residue or rice-straw after rice is harvested. In many parts of Gujarat there is a close integration between smallholder farmers' cattle or livestock rearing and crop production for rice-straw (Staal et al. 2006).[21]

Hence, one of the likely scenarios is that the rice-wheat farmers might grow a third summer crop, green fodder, and the tobacco farmer might replace the vegetable crop, say potato, with green fodder as well (Figure 19).

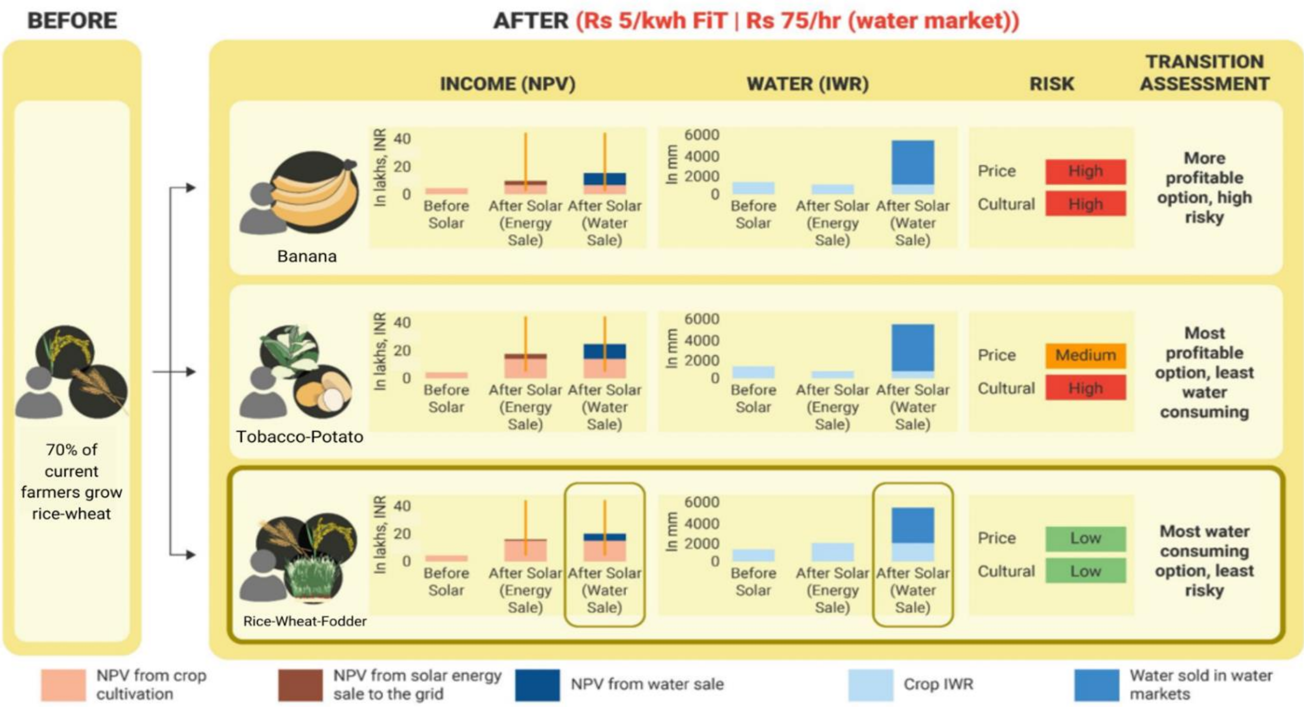

Figure 19. Options available to the rice-wheat farmer, and the choice most likely to be made.

[21] Staal et al. (2006). Smallholder Dairy Farmer Access to Alternative Milk Market Channels in Gujarat. Contributed Paper. 2006 IAAE Conference, Brisbane, Australia

Figure 19 shows the NPV estimates for two sets of choices:

- Farmers grew and sold crops and earned money from the sale of energy through net metering; and
- Farmers grew and sold crops and earned money from the sale of water in the active water markets.

It is clear that the rice-wheat farmer is likely to continue growing rice-wheat. The change we are likely to see is the addition of green fodder as a summer crop, now that they are able to tap enough water for the third season as well.

Between selling energy and selling water, farmers are more likely to sell water. This is because with the introduction of net metering, expert consultations suggested that the water markets have been hardening and responding to the FiTs. While this option is good for farmers financially, it might result in continued or excessive extraction of groundwater.

The evolution of crop choice in Anand spans over a few decades. For instance, there was no rice system in Anand 40 years ago. With the introduction of the canal system in the state, overall surface water supply increased, and with it, rice cultivation increased as well. So, the rice-wheat farmers are likely to continue growing rice-wheat, with the addition of a summer crop, alfalfa, which is fodder for the booming livestock industry in the district.

The second agent in this district is the tobacco-potato farmer, who is also unlikely to change crops after the introduction of solar irrigation (Figure 20).

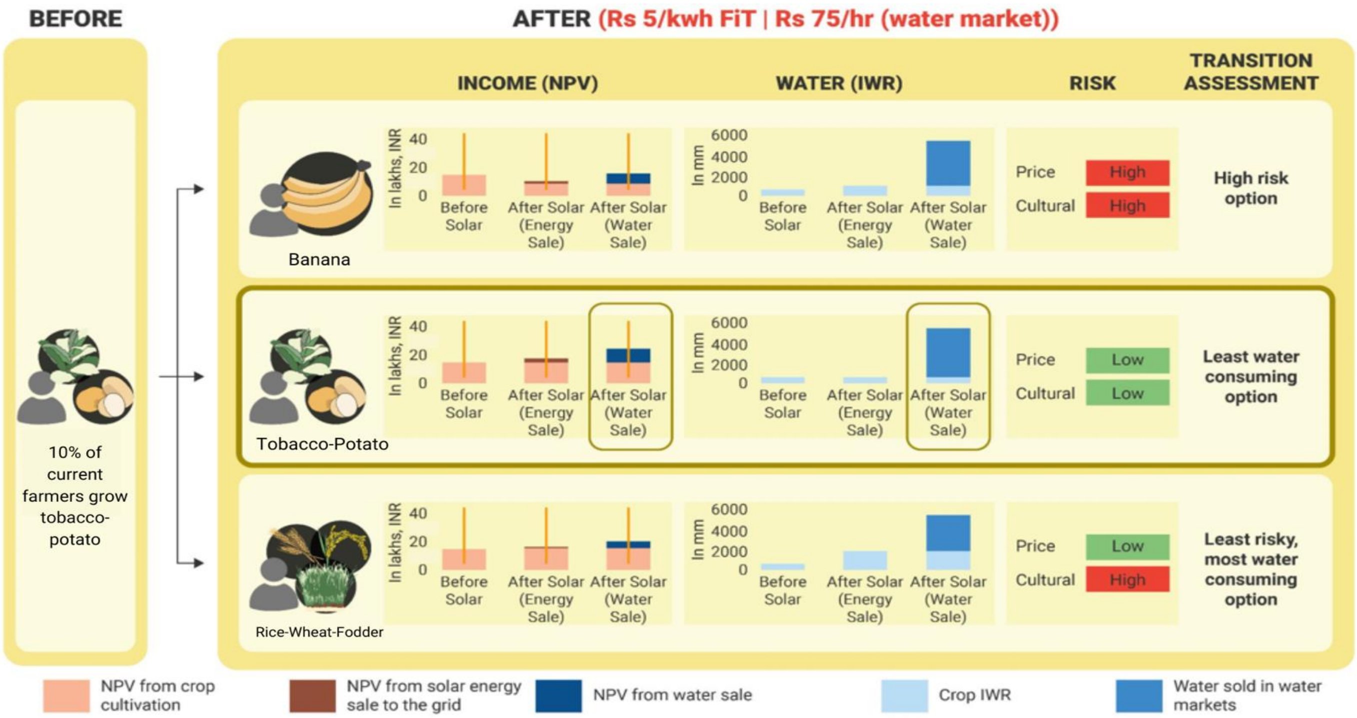

Figure 20. Options available to the tobacco-potato farmer, and the choice most likely to be made.

The tobacco-potato farmer is most likely to continue growing the same crops or, in some cases, switch from potato to green fodder. Apart from rice-wheat, tobacco is the second major crop in the district. There is a strong tobacco procurement system in place, especially in the Charotar area. If these farmers are not already growing a summer crop, they may grow either vegetables or green fodder during the summer.

Green fodder is the common denominator for both rice-wheat and tobacco-potato farmers because dairy is the major cash earner in this district. Most farmers in the district have cows and buffaloes. To ensure a high-quality milk supply, they need to have green fodder. However, Anand has no rainfall during the summer season, which means that they will be unable to grow their own fodder for these animals. Introducing solar irrigation here could allow farmers to grow green fodder like alfalfa as a summer crop (alfalfa requires irrigation every alternate day and could increase the cost of irrigation).

Some of the International Water Management Institute's (IWMI) own work in the region has shown that with the introduction of solar irrigation, there have been no major changes in crop choices, and there has only been an increase in livestock and green fodder.[22]

Currently, our modeling exercise seems to suggest that it is more profitable for farmers to earn from the sale of crop + sale of water, than from the sale of crop + sale of energy, at the assumed water rates and FiTS. The experts we consulted stated that there are two different classes of solar farm owners -- those that specialize in selling water and those who don't. The ones who do sell water have hired managers and have a systematic bookkeeping system to sell water. The amount of water and energy they use for their own consumption is very small. The second class of tubewell owners sell energy to the grid.

The crop choices of these two sets of farmers are currently unclear and require additional research.

When each of the individual agent/farmer decisions are added up, at the district level, the status quo is likely to result in high groundwater over abstraction. This is already the case in large parts of Gujarat. For a truly sustainable transition to occur, a substantial number of farmers must move away from cultivating rice-wheat to banana or other less water-intensive crops (Figure 21).

[22] Based on stakeholder consultations with IWMI staff in Anand, Gujarat.

	PERCENTAGE OF FARMERS					GW OVEREXPLOITATION ESTIMATIONS			
Crop	Rice-Wheat	Rice-Wheat-Green Fodder	Banana	Tobacco-Potato	Pearl Millet	Weighted & normalised IWR (in mm)	Total recharge (in mm) [RF - Recharge from rainfall, OS - Recharge from other sources]	GW exploitation status (in %)	Sustainability status
BEFORE	65%	-	20%	10%	5%	520		132%	Sustainable
AFTER (likely outcome)	-	65%	20%	10%	5%	766	RF - 103 OS - 291 Total - 394	195%	Comparatively less sustainable
AFTER (sustainable transition)	-	5%	10%	5%	80%	100		25%	Sustainable

Figure 21. Collective impact of individual agent decisions on Anand's groundwater abstraction status.

The results are slightly higher compared to CGWB's classification of the groundwater status of all eight blocks in the district as 'safe', indicating that abstraction is significantly lower than recharge. Our results are different from this and could be attributed to the assumptions we have made around irrigation water requirements for the field crops.

Solar irrigation may be an appropriate solution for this district only if the FiTs can compete with the existing water market tariffs. The FiTs have to be sufficiently high to discourage farmers from selling water and incentivize them to sell energy instead.

IWMI's work in the area has suggested that the yearly payback for the loans is high, despite the subsidies. This is especially true for farmers who are not selling electricity but are buying electricity from the grid at tariffs as high as INR 0.6/unit, in addition to the loan repayment. This has resulted in high electricity bills.

3.5. Botad, Gujarat: Introduction of solar irrigation with net metering and income from FiTs

In Botad, cotton is the most dominant crop and accounts for almost 80% of the area under cultivation. It is also the thirstiest crop in the district. This is followed by wheat, sorghum and groundnut, all of which comparatively require less water. We found that Botad is partially land constrained, water constrained, but with no energy constraints.

Although only 40% of the total cultivable area is irrigated (primarily through canals), district data suggest that soil salinity is a problem. Salinity constrains further expansion of irrigation and what can be grown (All Gujarat News 2021). Farmers in Botad must rely on basalt rock aquifers and must grow salt-tolerant crops. The average annual rainfall is low at around 400 mm in this region, much below the national average. In addition, Botad has access to grid-connected electricity.

In this situation, if we were to introduce solar irrigation in Botad, what crop choices are farmers likely to make; how will their incomes change and how will the groundwater depletion status change? The ABM suggests a 'sustainable transition' is theoretically possible where farmers could reduce the production of cotton and increase the production of groundnut, which requires less water. We consulted with water and agriculture experts to understand whether farmers would shift to less water-intensive crops, based on our model (Figure 22).

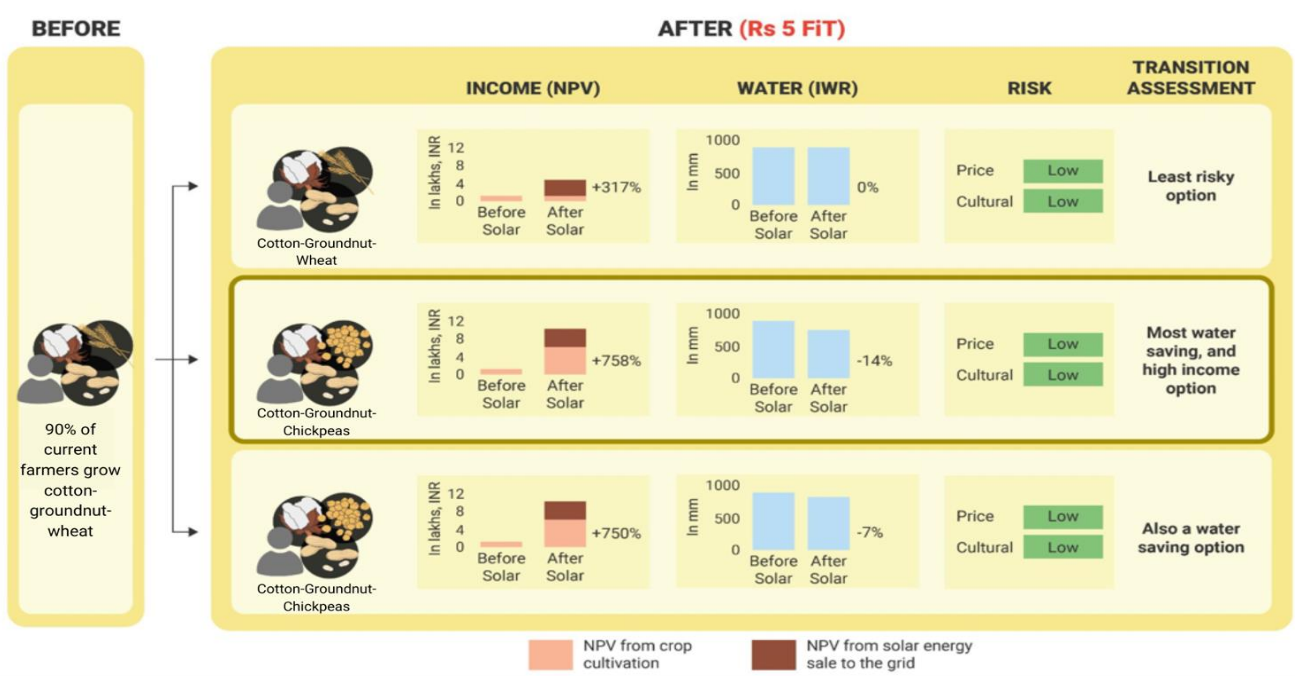

Figure 22. Options available to the cotton-groundnut farmer, and the choice most likely to be made. The difference between the second and third rows is that in the second, the

fraction of groundnut grown is greater than cotton, while in the third, both crops are grown in equal amounts.

The cotton farmer is likely to continue growing *Bt* (*Bacillus thuringiensis*) cotton during *kharif* and groundnut during *rabi*. Over the years, cotton farmers have transitioned from rainfed cotton to irrigated *Bt* cotton as the yield of *Bt* cotton is high and stable when fully irrigated. Farmers with no irrigation or deficit irrigation cannot grow *Bt* cotton in this region because of its high irrigation water requirement. In addition, one of the main drivers of crop choice for *Bt* cotton is the presence of cotton corporations and established systems of private trade.

Stakeholder consultations across both districts of Anand and Botad in Gujarat suggested that the MSP does not drive crop choice as the FCI procurement is minimal here. It is only in the last three to four years that the Gujarat government has started procuring pulses and groundnut, but these have been in insignificant quantities, or the process has been slow.[23]

Since there are established markets for the sale of *Bt* cotton, this crop will compete with energy sales. Farmers are likely to transition to selling energy in larger quantities only if the income from the sale of energy is significantly greater than the income from the sale of cotton.

When each of the individual agent/farmer decisions are added up, at the district level, the status quo is likely to result in high groundwater over abstraction (Figure 23). This is already the case in large parts of Botad. For a truly sustainable transition to occur, a substantial number of farmers must move away from cultivating cotton to groundnut or sesame or other less water-intensive crops. However, without established market linkages and demand for these other crops, there may not be sufficient uptake.

[23] Read more: https://www.thehindubusinessline.com/economy/agri-business/gujarats-groundnut-farmers-rue-slow-paced-procurement-high-rejections/article25726783.ece

	PERCENTAGE OF FARMERS			GW OVEREXPLOITATION ESTIMATIONS			
Crop	Cotton(50%)-Groundnut(50%)-Wheat	Cotton(50%)-Groundnut(50%)-Chickpeas	Cotton(25%)-Groundnut(75%)-Chickpeas	Weighted & normalised IWR (in mm)	Total recharge (in mm) [RF - Recharge from rainfall, OS - Recharge from other sources]	GW exploitation status (in %)	Sustainability status
BEFORE	80%	10%	10%	44		26%	Sustainable
AFTER (likely outcome)	80%	10%	10%	44	RF - 151 OS - 22 **Total - 173**	26%	Sustainable
AFTER (sustainable transition)	5%	15%	80%	9		5%	Sustainable

Figure 23. Collective impact of individual agent decisions on Botad's groundwater abstraction status.

Solar irrigation may be appropriate for this district only if the FiTs from selling energy to the grid can sufficiently compensate for income from sale of cotton. While we have accounted for only crop transitions in our modeling exercise, agrivoltaics is also a likely possibility in this district.

3.6. Nadia, West Bengal: Introduction of solar irrigation with no net metering and no income from FiTs

In Nadia, West Bengal, the dominant farmer grows rice during *kharif, rabi* and *zaid* (monsoon, post-monsoon and summer), and the rice grown during these three seasons are called *Aus*, *Boro* and *Aaman*, respectively. West Bengal is one of the unique cases in the country where farmers grow paddy all year round, enabled by its unique agroclimatic conditions, with high temperatures and heavy rainfall.

In Nadia, we found that it was energy that stood out as the major constraint, with no constraints around land and water availability.

Farmers in Nadia currently face an energy constraint. While most of West Bengal is fully electrified, farmers in some parts of the state, like Nadia, still rely on diesel pump sets for irrigation. Here, energy is expensive and adds to the cost of production. Depending on the crop, the cost of irrigation could be anywhere between 10-20% of the total cost of production.

Groundwater in Nadia is held in massive alluvial aquifers that economists call bathtub aquifers. In such a system, each individual farmer's water withdrawal has a relatively small impact on the water table as water moves quickly across the aquifer system. With these 'seemingly endless' bathtub aquifers (Srinivasan 2022), Nadia's farmers are not feeling the pinch of groundwater decline. Nadia experiences a high average annual rainfall of around 1,300-1,400 mm as per the Agriculture Contingency Plan for District: Nadia, West Bengal (2011) . Farmers in West Bengal have not been able to exploit groundwater resources because of the lack of access to grid-connected electricity. So, the aquifers in West Bengal are quite rich.

There is no land constraint in Nadia district as sufficient rainfed land (~40%) is available for expanding irrigation.

In this situation, if we were to introduce solar irrigation in Nadia, what crop choices are farmers likely to make; how will their income and groundwater depletion status change? The ABM suggests a 'sustainable transition' is theoretically possible where farmers could reduce the production of rice from three seasons to one or two seasons.

We consulted water and agriculture experts to understand whether farmers would shift to less water-intensive crops, based on our model.

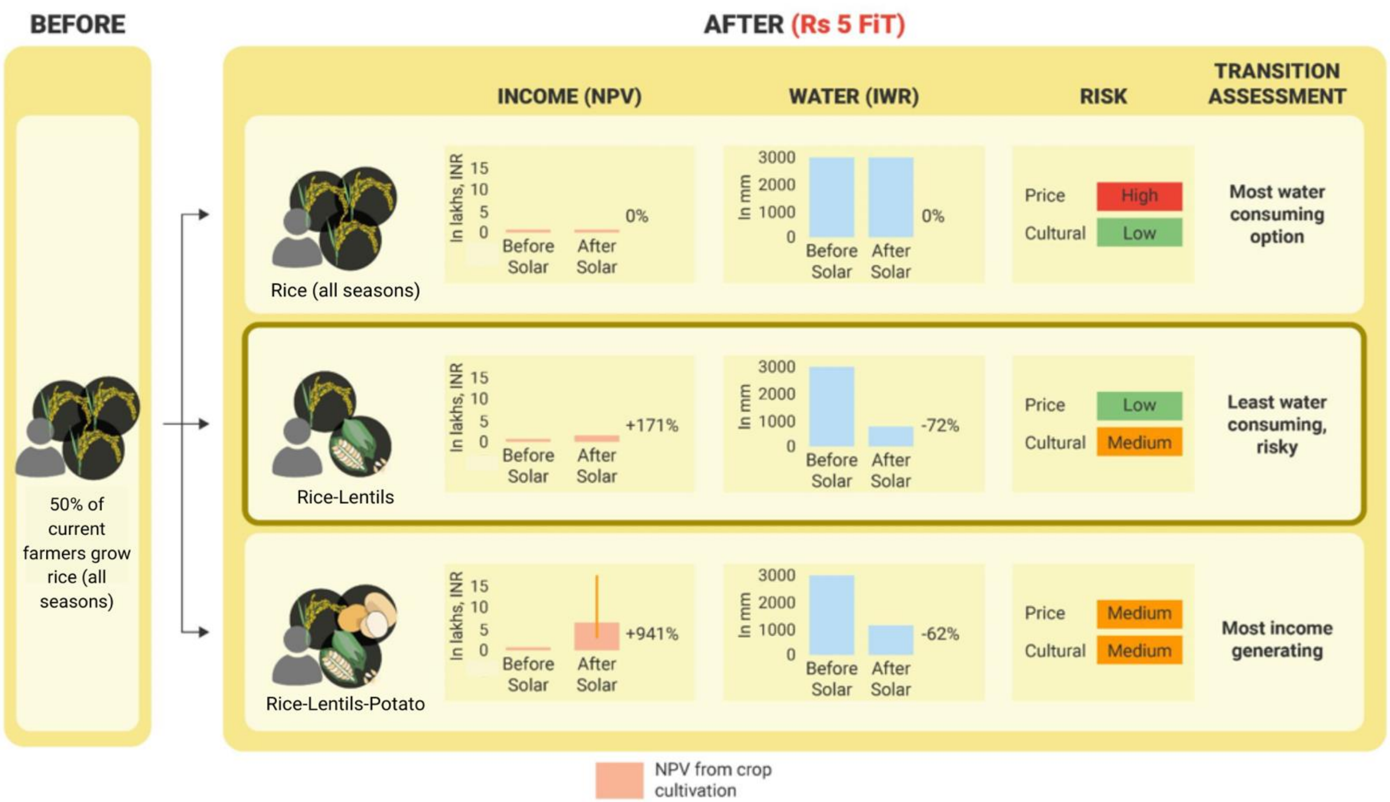

Figure 24. Options available to the rice farmer, and the choice most likely to be made.

In Figure 24, we can see that farmers are most likely to shift from growing rice in all three seasons to growing a combination of rice-lentils-potato (i.e., option 3, which is a combination of aus rice grown during *kharif*-lentils-potato).

The following factors are likely to drive farmers' choices in Nadia:

- **Monsoon delays**: Lackluster monsoons in recent years have caused farmers, particularly in the northern districts of West Bengal, to reconsider growing rice. Low or late northeast or southwest monsoons are typically associated with low yields. To hedge against this risk, farmers may shift to growing other crops that don't have high crop water requirements.
- **Inactive** Agricultural Produce Market Committees **(APMCs)**: While there are APMCs in West Bengal, they are not active. It is reported that West Bengal remains the only state in India to not have adopted Niti Aayog guidelines for setting up APMCs.[24] This basically means that there are no floor prices for the crops that these farmers sell. Similar to Bihar, there are some farmers who take their produce to sell in the

[24] Read more: https://www.financialexpress.com/india-news/west-bengals-no-to-apmc-act-centres-no-for-e-mandi/996059/

Punjab's APMCs. Some even cross the border and sell it in markets in neighboring countries like Bangladesh.

- **Rice cultivation alone has not been profitable for farmers**: Currently, irrigation costs are quite high in West Bengal because farmers depend on diesel pump sets. This makes it almost financially unsustainable to continue growing rice across all three seasons. Stopping rice farming for even one of the seasons can prove to be profitable for farmers, as long as there is a sufficient market for the alternative crop, which could be lentils and oilseeds or vegetables like potato, all of which require significantly less water compared to rice.

In this district, farmers need to discontinue cultivating rice since a large number of blocks in the district have overexploited groundwater. As Figure 25 estimates, switching to a combination of rice in one season and other crops like lentils and/or vegetables in other seasons could be a win-win for the farmer's income and the environment, with reduced irrigation water requirement.

	PERCENTAGE OF FARMERS			GW OVEREXPLOITATION ESTIMATIONS			
Crop	Rice (*Kharif-Rabi-Zaid*)	Rice-Lentils	Rice-Lentils-Potato	Weighted & normalised IWR (in mm)	Total recharge (in mm) [RF - Recharge from rainfall, OS - Recharge from other sources]	GW exploitation status (in %)	Sustainability status
BEFORE	50%	30%	20%	1417		348%	Unsustainable
AFTER (likely outcome)	50%	30%	20%	1417	RF - 310 OS - 98 Total - 408	348%	Unsustainable
AFTER (sustainable transition)	10%	50%	40%	843		207%	Comparatively more sustainable

Figure 25. Collective impact of individual agent decisions on Nadia's groundwater abstraction status.

Solar irrigation may be the right solution for this district as it will reduce the cost of irrigation and allow farmers to add a third summer crop (that is not rice), all of which would boost farmer incomes in the state.

4. LEARNINGS, LIMITATIONS AND NEXT STEPS

4.1. Learnings

4.1.1 *Both biophysical and socioeconomic factors influence the outcomes of introducing solar irrigation*

Access to grid electricity and markets as well as fundamental resource endowments -- rainfall and aquifers -- are important determinants of the outcomes of introducing solar irrigation

Although Punjab and Bihar are both alluvial in nature, the following make rice-wheat cultivation more sustainable in Bihar when compared to Punjab:

- ***Access to grid-connected electricity***: Farmers in Punjab have access to free grid-connected electricity, while most farmers in Bihar only have access to diesel pump sets. This means that farmers in Bihar have not been able to exploit groundwater resources as much and for as long as those in Punjab.[25]

- ***Difference in rainfall***: Most parts of Bihar get high rainfall (as much as 1200 mm and greater) when compared to most parts of Punjab which has been receiving less than 500 mm over the years.

- ***Access to APMCs***: Farmers in Punjab have had access to strong APMC networks, allowing them to get assured returns for their produce. However, the Bihar government scrapped the APMC Act in 2006 with the expectation that it would drive private investments in the state's agricultural sector and improve the livelihoods of its poor farmers. However, most studies have shown that this has not been the case.[26] The scrapping of APMCs has exposed farmers to severe market volatility and resulted in low growth rates in the agricultural sector (Himanshu 2020).[27]

  The APMC Act was replaced by the Primary Agricultural Credit Societies (PACS), a designated agency for the procurement of rice alone and meant to eliminate middlemen in paddy procurement. However, reports suggest that the PACS have

[25] In our economic calculations we have accounted for the reduction in costs of switching from diesel to solar energy. One of the caveats is that often replacing diesel pumps with solar pumps does not automatically mean that they will be grid connected. Diesel pumps are typically located in remote regions without grid access, hence replacing them with solar pumps does not guarantee grid connection.
[26] Read more: https://www.outlookindia.com/website/story/india-news-nitish-kumars-govt-scrapped-apmc-act-14-years-ago-but-farmers-in-bihar-still-languishing/378104
[27] Read more: https://www.livemint.com/opinion/columns/lessons-from-bihar-s-abolition-of-its-apmc-system-for-farmers-11600962615201.html

not played any role in rice procurement over the years.[28] Reports also suggest that rice is transported from Bihar to be sold in APMCs in Punjab.

Compared to Punjab, solar irrigation may be the right solution for Bihar. It will reduce the cost of irrigation while simultaneously boosting incomes in this state; while at the same time ensuring groundwater sustainability, since the biophysical characteristics of Bihar, with its rich alluvial soils and heavy rainfall, is different from that in Punjab.

4.1.2 *Implications of introducing solar irrigation vary with land, energy and water constraints*

Regions that are land limited because they are 100% irrigated have potential for sustainable transitions if accompanying agricultural policies are changed and FiTs are attractive. Otherwise, they may see decarbonization but no change in groundwater use.

While Bathinda has no further agricultural land available for irrigation and hence cultivation, Anand is only partially land limited. This means that farmers can make choices only within their farms and there is no additional land they can lease and cultivate with the availability of solar irrigation. Across both districts we see demand driving crop choices. The existence of MSPs for rice-wheat in Bathinda has locked farmers in cultivating the same.

The two Gujarat cases are slightly atypical. In Anand, the dairy industry's demand for fodder has ensured that farmers continue growing rice-wheat, with the addition of green fodder as a third crop.

Regions limited by energy are most likely to see further intensification. There is an opportunity to avoid "lock-ins" through policy design here.

The energy-limited regions lack access to the grid, but this is also changing rapidly. While farmers in both West Champaran and Nadia are currently using diesel as the main source of energy for irrigation, most districts in both states – Bihar and West Bengal – are currently almost fully electrified, i.e., connected to the grid.

How much of this electricity is available to farmers needs to be studied further. Introducing solar irrigation in these districts could potentially reduce the cost of irrigation for these farmers where they switch from diesel to solar. Since both districts have similar agroclimatic conditions, like high rainfall, continuing to grow rice-wheat, along with the introduction of a third crop, may be a sustainable option for them. Districts like Nadia already have a third (summer) crop.

[28] Read more: https://www.indiatoday.in/india/story/bihar-records-growth-in-farm-yield-post-apmc-act-but-farmers-unhappy-1748437-2020-12-10 and https://thewire.in/agriculture/punjab-mandis-farmer-produce-up-bihar

Regions limited by water are most likely to see the emergence of agrivoltaics. Both Bengaluru Rural in Karnataka and Botad in Gujarat are water constrained because of the nature of their hard rock aquifers. In addition, Botad also suffers from salinity-related problems. In both cases, agrivoltaics can be a real possibility for the farmers.

Both Bengaluru Rural and Botad differ in the proportion of rainfed to irrigated farmers, with the former having a higher percentage of rainfed farmers. Rainfed farmers in Bengaluru Rural cultivating finger millet are likely to switch to agrivoltaics if sufficient financing is available to help them set it up. Finger millet is not profitable despite having MSPs because the APMCs do not procure them in sufficiently large quantities. Hence, switching to agrivoltaics may be more profitable for the farmer.

Irrigated farmers across Bengaluru Rural and Botad are purely driven by market demand. Rise in arecanut prices in Bengaluru Rural has pushed a large number of farmers towards its cultivation. Since land is not a constraint in the district, farmers have been seen leasing additional parcels of land to grow this crop. Similarly, in Botad, the cotton industry drives the demand for cotton, which has been a profitable cash crop for farmers. In both districts, unless there are other lucrative crops available, it would be challenging to get them to switch their current practices.

Box 2. Historical Changes in Depth to Groundwater and Implications for Sustainable Transitions

Figure 26 shows the changes in depth to groundwater over the years. What's notable is that the Bathinda (Punjab) trendline is rising while the West Champaran (Bihar) line has been more or less static over the past few decades. This is because rainfall has declined and overabstraction has increased over the years in most parts of Punjab, resulting in precipitous drops in groundwater levels. However, in Bihar, in contrast, lack of access to grid-connected electricity and high recharge has kept most parts of the state within 'safe' limits. This means that continuing to grow rice-wheat in Bihar is not half as damaging as cultivating the same crop combination in Punjab.

Further, the difference in groundwater levels in different aquifer types is stark. For instance, the hard rock aquifer regions in Bengaluru Rural vary drastically year after year, while the alluvial aquifers in Bathinda and West Champaran are smoother, indicating how the nature of the aquifer determines variability in groundwater levels.

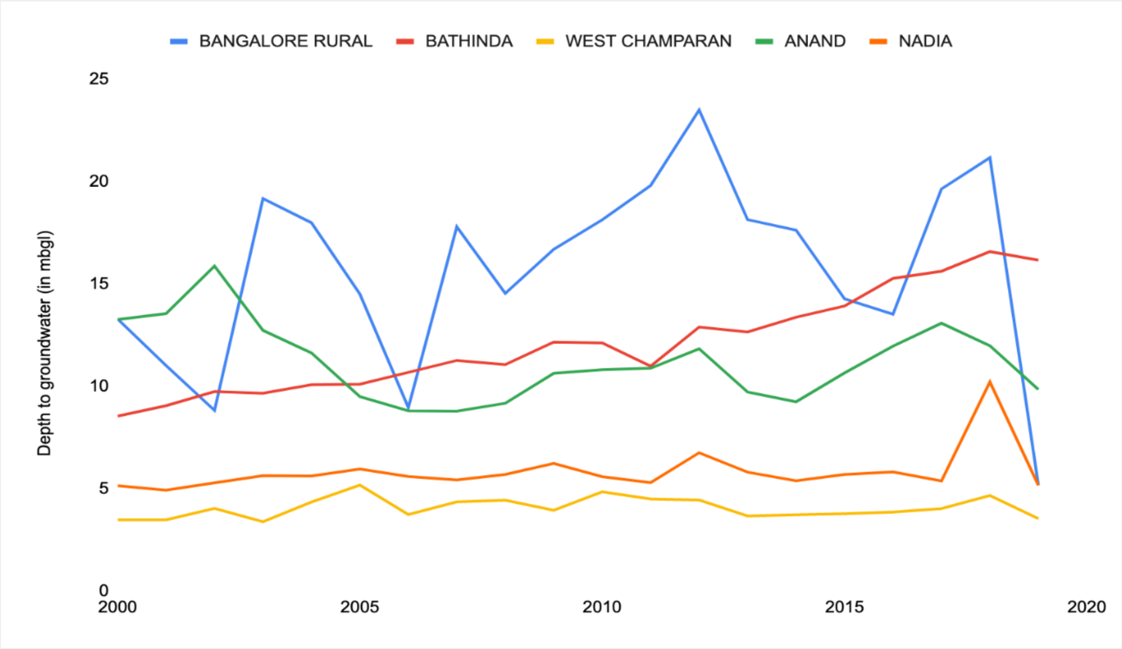

Figure 26. Fluctuations in groundwater level (from CGWB) over a 20-year period (Box 2) across five districts in the case study. The units in the y axis are in meters below ground level (mbgl)
Source: CGWB, downloaded from India Water Resources Information System (IWRIS), accessed on 15 January 2023

Note: Data for Botad is not available since the district was formed recently.

4.1.3 *Neither rationing nor pricing guarantee sustainability of groundwater*

India needs a new water pricing regime. Even though electricity is fully free or subsidized, there is still some element of control or rationing because state governments typically give only 6-8 hours of electricity every day. This 'rationing' sets an informal limit on the amount of water farmers can extract. However, these limits often do not take into consideration the biophysical constraints that already exist in this region. For instance, farmers in Punjab could use a 10 HP (1 horsepower = 746 watts) pump to draw water from shallow tubewells, whereas their counterparts in hard rock aquifer regions in Karnataka would use higher HP pump sets to pump water from greater depths; and they could still be pumping more water than is sustainable for that district or region.

Drawing water in Punjab is very different from that in Karnataka, because while there are no immediate biophysical constraints in the former, overdrawing in parts of Karnataka could quickly result in borewells drying up (as explained earlier using the bathtub and egg carton analogy).

The challenge in the current rationing regime is that while fixing the number of hours of electricity supply, we still don't know the demand for water. The demand for water tends to be highly variable, which means that the pricing also ends up being variable. This variable demand and price result in the extraction of quantities of groundwater that may be above sustainable limits for a region.

In another example, most farmers in Bengaluru Rural district get only 4 hours of electricity. They use all 4 hours to extract large quantities of water for arecanut, a water-guzzling crop. Even in this case, although there are limits to energy, farmers were not discouraged from pumping as much water as they can.

Solar irrigation provides the opportunity to introduce a pricing regime. It is different from the rationing regime because there is an opportunity cost for water here, especially with the introduction of FiTs. This allows farmers to consider economically feasible alternatives, and, also, allows the government to tide over the political non feasibility of ever doing away with incentives like electricity subsidies for agriculture.

However, this regime transition alone will not be sufficient to encourage the transition to less water-consuming crops. An entire set of systemic changes will have to occur for farmers to transition out of their current production practices, which brings us to lock-ins in agriculture.

4.1.4 *Breaking lock-ins in agriculture for sustainable transitions*

The regime transition we described above is not easy. It is challenging to move away from the status quo because there are lock-ins in agriculture. Lock-ins are often described as 'self-reinforcing mechanisms that reproduce the status-quo and impede change' Weituschat (2022). This perfectly describes the agricultural ecosystem in the country. Farmers who grow some crops continue growing the same crops year after year.

There are many reasons for these lock-ins:

- There is an investment path dependency in agriculture, which means that conventional agricultural methods have developed over centuries based on investments in very specific skills and expertise, and shifting to new methods of farming would require additional investments, which farmers may not be willing to make.

- There is compartmentalized thinking that results in different agricultural disciplines being studied in silos; this is especially true of the green revolution, where high yields came at the expense of reduced biodiversity.

- Lock-ins arise because success is measured only in economic terms, either through yields or returns from the sale of crops. Often measures of success don't account for ecological or environmental indicators which, if not measured or tracked, could have adverse consequences for the ecosystem.[29]

However, these lock-ins in agriculture can be broken through socio-technical evolutions. This means the entire system must be set up for change right from production to consumption. In addition, the policy environment should also support this evolution. Piecemeal approaches to change have often resulted in adverse consequences.

For instance, to break the rice-wheat cultivation pattern in Haryana, the state government introduced maize in their MSP. For the first three years of its introduction, large tracts of land (almost 100,000 ha) were converted to maize cultivation. The government procured this maize through APMCs in the first three years. However, since there was insufficient demand for it, they were only stored in Haryana's granaries. The government was unable to distribute them in their markets. Eventually, the farmers stopped producing maize since procurement did not match production.

There is also a positive outlier where a state government focused on creating an ecosystem for transitioning to millets. The Odisha Millet Mission is an example of how socio-technical evolutions are necessary for making large sustainable transitions.[30] What the Odisha government did differently was not only to offer MSPs for millets but also ensure the complete procurement and distribution of the millets. They encouraged the consumption of millets at the local level by introducing them in the Public Distribution System (PDS), Integrated Child Development Scheme (ICDS) and the Midday Meal Scheme. This ensured that demand and supply matched.

4.1.5 *Simulation tools can help anticipate system responses before large-scale programme implementation*

As discussed earlier, simulations offer early insights into the different outcomes that could emerge based on different conditions -- agroclimatic, hydrological, socioeconomic and policy. Each of these conditions or constraints will influence choices and outcomes across multiple locations differently. Standard evaluation methods like Randomized Control Trials (RCTs) will not be able to capture this until after project implementation. Simulations will then become particularly important before large-scale roll out of programmes so that we can account for unintended consequences in thoughtful ways in the planning process itself.

[29] Read more here: https://www.wri.org/climate/expert-perspective/path-dependence-and-carbon-lock-agriculture-sector
[30] Read more here: https://milletsodisha.com/

4.2. Limitations of the Study and Scope for Improvement

4.2.1 *Methods*

- **We can't predict the future perfectly:** Simulations offer a plethora of outcomes, but which outcomes have high probabilities have been arrived at based on consultations with experts who work in these regions. Their insights are based on current socio-technical evolutions. While human behavior is not perfectly predictable, there may be 'black swan' events, which are developments that occur in these ecosystems that may completely change the trajectory, rendering the outcomes we have outlined here void. Climate change in particular offers such a possibility.
- **Diffusion of knowledge (a key ABM feature) not accounted for:** One of the key features of ABMs is that it accounts for interactions between agents, in this case farmers, and how that interaction affects decision making. In the interest of simplicity, we did not account for these interactions between farmers.
- **Focus on crop transitions and not irrigation technologies:** In this study, the focus of the models has been on changes in crop choices, without accounting for changes in irrigation technologies. Accounting for the latter will have an impact on both farmer economics as well as the irrigation water requirement estimations. This can be accounted for as an input parameter in subsequent studies.
- **Focus on income from sale of crop cultivation and sale of energy:** In this study, we limited the scope of the farm scale economics to only income from crop cultivation and sale of energy to the grid. However, the Situation Assessment Survey (2021) results show that income from crop cultivation constitutes only 37% of the share in a farmer's income, and there are other sources of income including livestock, wages and salaries from other farm work and nonfarm business.[31] Future models could incorporate these additional sources of income as well.
- **Focus on a partial equilibrium model:** Through this study, we kept the agent at the center of discussion, limiting the model to only one actor. However, one of the important actors in solar irrigation projects, especially those with net metering, is the local DISCOM which is responsible for evacuating the excess

[31] Rai Vinaykumar. (2021). Economic Survey: Average monthly income per agricultural household at Rs 10,218. Businesstoday. Retrieved from: https://www.businesstoday.in/latest/economy/story/economic-survey-average-monthly-income-per-agricultural-household-at-rs-10218-320921-2022-01-31 [Accessed on 25 May 2023]

energy generated and paying for net metering as well. We did not include the DISCOM in our model since it is currently outside the scope of our work.

- **Direct Benefit Transfers (DBT) not included:** We didn't include this in our modeling exercise.

4.2.2 *Datasets*

- **Economic datasets are from government and private sources:** For data around yield, cost of production and revenue from sale of produce, we used government and private data sources. These may not be fully accurate, and it's important to note that there will be margins of error (as a part of this project, we will not be able to estimate the magnitude of those errors). However, this does not take away from the methodology or the framework. Rough estimates from these sources have allowed us to study these districts of interest to some level of accuracy.

4.3. The Way Forward

We believe that this work can move forward in two ways:

- **Assist with PM-KUSUM planning:** If a state is in the midst of solar irrigation implementation, through PM-KUSUM or otherwise, we can answer key questions regarding what the right pump size is or FiT might be so that the scheme does not result in unintended consequences. Our simulation model allows us to model scenarios and quantify farmer-level impacts (economic) and district-level impacts (i.e., collective impact of individual farmer decisions on the district's groundwater status) that can then be used to understand where this scheme can be implemented without worsening groundwater depletion.
- **Method for building farm futures modeling:** As a continuation of this work, we will be developing a similar data-based model for a few other agricultural practices like agroforestry (with or without carbon financing), agrivoltaics and solar irrigation, protective irrigation, multilayer cropping and the one-acre model, drip irrigation, regenerative agriculture, agro-tourism and value addition. We plan to do this exercise across a few districts in peninsular India to understand farmer scenarios available for different practices and the choices farmers are likely to make.

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5. Annexes - Data for all case studies

Bathinda, Punjab

a. District profile

I. **Energy constraint**

Indicator 1: Source of energy	Electric	Diesel	Windmills	Solar	Manual/animal	Others	Total
Deep tubewell	12,314	1,997	3	0	0	0	14,314
Medium tubewell	20	2	0	0	0	0	22
Shallow tubewell	28,925	6,104	32	4	0	9	35,074

Source: Fifth Minor Irrigation Census (2013-14), http://164.100.229.38/state-wise-reports?shs_term_node_tid_depth_1=81&shs_term_node_tid_depth=125

Indicator 2: Average hours of pumping/day	(a) *Kharif* season					
	0-4 hrs	4-8 hrs	8-12 hrs	12-16 hrs	16-20 hrs	20-24 hrs
Deep tubewell	46	5,123	9,714	3	3	5
Medium tubewell	0	18	4	0	0	0
Shallow tubewell	1,617	21,910	12,422	121	64	25

Source: Fifth Minor Irrigation Census (2013-14), http://164.100.229.38/state-wise-reports?shs_term_node_tid_depth_1=81&shs_term_node_tid_depth=125

Indicator 2: Average hours of pumping/day	(b) *Rabi* season					
	0-4 hrs	4-8 hrs	8-12 hrs	12-16 hrs	16-20 hrs	20-24 hrs
Deep tubewell	81	14,334	476	1	1	1
Medium tubewell	1	18	3	0	0	0
Shallow tubewell	1,432	31,264	3,373	49	36	5

Source: Fifth Minor Irrigation Census (2013-14), http://164.100.229.38/state-wise-reports?shs_term_node_tid_depth_1=81&shs_term_node_tid_depth=125

II. Water constraint

Indicator 1: Aquifer type	Alluvium

Source: Principal Aquifers of India, CGWB, Ministry of Jal Shakti. Available at: https://cgwb.gov.in/Maps.html; accessed on 21 April 2023

Indicator 2: Distribution of tubewells based on depth	0-20 m	20-40 m	40-60 m	60-70 m	70-90 m	90- 110 m	110-130 m	130-150 m	> 150 m
Deep tubewell	0	0	0	0	9,221	4,953	300	6	415
Medium tubewell	0	5	14	3	0	0	0	0	0
Shallow tubewell	36,113	51	0	0	0	0	0	0	0

Source: Fifth Minor Irrigation Census (2013-14), http://164.100.229.38/state-wise-reports?shs_term_node_tid_depth_1=81&shs_term_node_tid_depth=125

III. Land constraint

Indicator 1: Percentage of land irrigated	99.80%

Source: Farmer's portal, https://farmer.gov.in/irrigated.aspx

b. District crop profile to identify agent farmers

Crop	Area under cultivation (in 1000 ha)	Area irrigated (in 1000 ha)	Area under cultivation as a % of total area
Wheat	556	556	46.55%
Rice	388.94	389	32.56%
Cotton	168.88	168.96	14.14%
Fodder	56	55.99	4.69%
Potato	10.46	10.46	0.88%
Citrus	5	5	0.42%
Sesame	3.92	0.03	0.33%
Minor pulse	2.77	0.52	0.23%
Barley	1.58	1.47	0.13%
Pearl millet	0.6	0.62	0.05%
Chickpea	0.23	0.22	0.02%
Pigeonpea	0.1	0.22	0.01%
Groundnut	0.03	0.05	0.00%
Kharif sorghum	0	0	0.00%
Rabi sorghum	0	0	0.00%
Sorghum	0	0	0.00%
Maize	0	0.38	0.00%
Finger millet	0	0	0.00%
Pulse	0	0.96	0.00%
Linseed	0	0	0.00%
Sugarcane	0	0.17	0.00%
Total	1,194.51		

Source: http://data.icrisat.org/dld/src/crops.html

c. Economics and water-related data, assumptions and estimations

Crop type	*Kharif*	*Rabi*	*Zaid*	Annual	Crop	Cost of cultivation (INR/acre)[a]	Yield (kg/ acre)	MSP	Price (INR/kg)	Revenue (INR/acre)	Profit (INR/ acre)	Crop water requirement (mm)	Effective rainfall mm)	Irrigation water requirement (mm)
Cereal		Yes			Wheat	28,787	5,789	Yes	20.15	116,657.8947	87,871	550	16	534
Cereal	Yes				Rice	20,282	3,000	Yes	19.4	58,200	37,918	1,400	204.8	1,195
Cash	Yes				*Bt* Cotton	24,464	809	Yes	57.26	46,323.34	21,860	1,000	204.8	795
Fruit	Yes				Fodder -	4,836	25,000	No	5	125,000	120,164	1,200	204.8	995
Vegetable		Yes			Potato	35,000	12,500	No	15	187,500	152,500	600	16	584
Fruit				Yes	Citrus	15,709	8,500	No	25	212,500	196,791	1,000	210	790

Note: [a] 1 acre = 0.040685642 hectares.

d. Sensitivity analysis

		Farmer 1			Farmer 2		
FiT (INR/ kWh)	Subsidy (center + state) (%)	Rice-wheat to rice-wheat (%)	Rice-wheat to cotton-potato (%)	Rice-wheat to kinnow (%)	Cotton-potato to cotton-potato (%)	Cotton-potato to rice-wheat (%)	Cotton-potato to kinnow (%)
	30	-10	33	-4	-4	-35	-30
3.5	50	-4	38	2	0	-31	-27
	70	-2	44	8	4	-27	-22
FiT 2	30	-3	41	7	1	-30	-23
5	50	-2	46	12	6	-26	-19
	70	8	52	18	10	-22	-15
FiT 3	30	5	51	20	9	-24	-13%
7	50	11	57	26	13	-20	-9
	70	16	63	32	17	-16	-5

West Champaran, Bihar

a. District profile

I. Energy constraint

Indicator 1: Source of energy	Electric	Diesel	Windmills	Solar	Manual/ animal	Others	Total
Deep tubewell	19	446	0	0	0	126	591
Medium tubewell	401	6,250	55	5	0	2,216	8,927
Shallow tubewell	136	4,312	8	11	0	1,269	5,736

Source: Fifth Minor Irrigation Census (2013-14), http://164.100.229.38/state-wise-reports?shs_term_node_tid_depth_1=81&shs_term_node_tid_depth=125

Indicator 2: Average hours of pumping/day	(a) *Kharif* season					
	0-4 hrs	4-8 hrs	8-12 hrs	12-16 hrs	16-20 hrs	20-24 hrs
Deep tubewell	327	142	108	15	4	10
Medium tubewell	4,279	1,870	2,560	595	38	65
Shallow tubewell	1,748	1,069	2,700	496	33	43

Source: Fifth Minor Irrigation Census (2013-14), http://164.100.229.38/state-wise-reports?shs_term_node_tid_depth_1=81&shs_term_node_tid_depth=125

Indicator 2: Average hours of pumping/day	(b) *Rabi* season					
	0-4 hrs	4-8 hrs	8-12 hrs	12-16 hrs	16-20 hrs	20-24 hrs
Deep tubewell	354	168	61	21	2	0
Medium tubewell	4265	2243	2005	790	52	52
Shallow tubewell	1750	1480	2067	706	50	36

Source: Fifth Minor Irrigation Census (2013-14), http://164.100.229.38/state-wise-reports?shs_term_node_tid_depth_1=81&shs_term_node_tid_depth=125

II. Water constraint

Indicator 1: Aquifer type	Alluvium

Source: Principal Aquifers of India, CGWB, Ministry of Jal Shakti. Available at: https://cgwb.gov.in/Maps.html; accessed on 21 April 2023

Indicator 2: Distribution of tubewells based on depth	0-20 m	20-40 m	40-60 m	60-70 m	70-90 m	90-110 m	110-130 m	130-150 m	> 150 m
Deep tubewell	0	0	0	0	17	82	425	38	44
Medium tubewell	0	186	8,708	522	0	0	0	0	0
Shallow tubewell	3,570	2,522	0	0	0	0	0	0	0

Source: Fifth Minor Irrigation Census (2013-14), http://164.100.229.38/state-wise-reports?shs_term_node_tid_depth_1=81&shs_term_node_tid_depth=125

III. Land constraint

Indicator 1: Percentage of land irrigated	69.28%

Source: Farmer's portal, https://farmer.gov.in/irrigated.aspx

b. District crop profile to identify farmer agents

Crop	Area under cultivation (in 1000 ha)	Area irrigated (in 1000 ha)	Area under cultivation as a % of total cultivation
Rice	401.13	201.87	40.28%
Wheat	221.16	208	22.21%
Sugarcane	166.97	162.7	16.77%
Maize	88.6	48	8.90%
Minor pulse	37.64	1.06	3.78%
Vegetable	35.09		3.52%
Potato	18.04		1.81%
Fruit	17.46	32.45	1.75%
Rapeseed and mustard	6.57		0.66%
Pigeonpea	1.63		0.16%
Onion	1.54		0.15%
Chickpea	0.01		0.00%
Total	995.84		

Source: http://data.icrisat.org/dld/src/crops.html

c. Economics and Water related data, assumptions and estimations.

Crop type	Cereal	Cereal	Cash	Cereal	Vegetable	Fruit	
Kharif	Yes			Yes			
Rabi		Yes			Yes		
Zaid							
Annual			Yes			Yes	
Crop	Rice	Wheat	Sugarcane	Maize	Potato	Mango	Minor pulses
Cost of cultivation (INR/acre)[a]	15,229	15,000	35,425	15,000	70,000	112,000	12,975
Yield (kg/acre)	2,100	3,700	25,000	6,000	14,000	6,000	408.75
MSP	Yes	Yes	Yes	Yes	No	No	MSP
Price (INR /kg)	19	20	10	19	23	150	55
Revenue (INR/acre)	40,740	73,075	250,000	112,200	322,000	900,000	22,481.25
Profit(INR/acre)	25,511	58,075	214,575	97,200	252,000	788,000	9,506.25
Crop water requirement (mm)	1,400	550	2,000	550	600	600	500
Effective rainfall (mm)	938	0	1,056	938	0	1,056	135
Irrigation water requirement (mm)	462	550	944	0	600	0	365

Note: [a] 1 acre = 0.040685642 hectares.

d. Sensitivity analysis

		Farmer 1			Farmer 2		
FiT (INR/kWh)	Subsidy (centre + state) (%)	Rice-wheat to rice-wheat-minor pulses (%)	Rice-wheat to sugarcane (%)	Rice-wheat to maize-potato (%)	Sugarcane to sugarcane (%)	Sugarcane to maize-potato (%)	Sugarcane to rice-wheat (%)
None		0	145	311	-4	59	-66
	30						
3.5	50						
	70						
FiT 2	30						
5	50						
	70						
FiT 3	30						
7	50						
	70						

Bengaluru Rural, Karnataka

a. District profile

I. Energy constraint

Indicator 1: Source of energy	Electric	Diesel	Windmills	Solar	Manual/ animal	Others
Deep tubewell	3716	12	0	1	0	7
Medium tubewell	7126	16	0	3	0	12
Shallow tubewell	3830	6	0	1	0	27

Source: Fifth Minor Irrigation Census (2013-14), http://164.100.229.38/state-wise-reports?shs_term_node_tid_depth_1=81&shs_term_node_tid_depth=125

Indicator 2: Average hours of pumping/day	(a) *Kharif* season					
	0-4 hrs	4-8 hrs	8-12 hrs	12-16 hrs	16-20 hrs	20-24 hrs
Deep tubewell	1,475	1,966	1,179	14	1	7
Medium tubewell	3,880	3,381	841	65	8	102
Shallow tubewell	2,424	2,283	598	8	6	17

Source: Fifth Minor Irrigation Census (2013-14), http://164.100.229.38/state-wise-reports?shs_term_node_tid_depth_1=81&shs_term_node_tid_depth=125

Indicator 2: Average hours of pumping/day	(b) *Rabi* season					
	0-4 hrs	4-8 hrs	8-12 hrs	12-16 hrs	16-20 hrs	20-24 hrs
Deep tubewell	1,934	2,530	172	2	0	4
Medium tubewell	3,461	4,119	535	82	37	43
Shallow tubewell	2,123	2,706	477	16	3	11

Source: Fifth Minor Irrigation Census (2013-14), http://164.100.229.38/state-wise-reports?shs_term_node_tid_depth_1=81&shs_term_node_tid_depth=125

II. Water constraint

Indicator 1: Aquifer type	Basement Gneissic Complex

Source: Principal Aquifers of India, CGWB, Ministry of Jal Shakti. Available at: https://cgwb.gov.in/Maps.html; accessed on 21 April 2023

Indicator 2: Distribution of tubewells based on depth	0-20 m	20-40 m	40-60 m	60-70 m	70-90 m	90-110 m	110-130 m	130-150 m	> 150 m
Deep tubewell	0	0	0	0	133	184	229	130	4023
Medium tubewell	0	151	6595	1603	0	0	0	0	0
Shallow tubewell	236	5206	0	0	0	0	0	0	0

Source: Fifth Minor Irrigation Census (2013-14), http://164.100.229.38/state-wise-reports?shs_term_node_tid_depth_1=81&shs_term_node_tid_depth=125

III. Land constraint

Indicator 1: Percentage of land irrigated	19.63%

Source: Farmer's portal, https://farmer.gov.in/irrigated.aspx

b. District crop profile to identify farmer agents

Crop	Area under cultivation (in 1000 ha)	Area irrigated (in 1000 ha)	Area under cultivation as a % of total area
Finger millet	125	2	54.01%
Fruits	37	19	16.06%
Minor pulses	20	0	8.67%
Maize	13	2	5.49%
Vegetables	11		4.60%
Fodder	7	4	3.19%
Pigeonpea	5	0	2.29%
Rice	5	5	2.26%
Sesame	2		1.01%
Castor	2		0.98%
Groundnut	2	0	0.74%
Rapeseed and mustard	1		0.27%
Potato	1		0.22%
Sugarcane	0		0.09%
Chickpea	0	0	0.06%
Pearl millet	0		0.04%
Onion	0		0.04%
Sunflower	0	0	0.00%
Total	232		

Source: http://data.icrisat.org/dld/src/crops.html

c. Economics and Water related data, assumptions and estimations

Crop type	*Kharif*	*Rabi*	*Zaid*	Annual	Crop	Cost of cultivation (INR/acre)[a]	Yield (kg/acre)	MSP	Price (INR/kg)	Revenue (INR/acre)	Profit (INR/acre)	Crop water requirement (mm)	Effective rainfall (mm)	Irrigation water requirement (mm)
Cereal	Yes				Finger millet	17,692	700	Yes	33.7	23,590	5,898	350	319	31
Fruit/vegetable				Yes	Arecanut	500,000	2,200	No	545	1,199,000	699,000	1200	319	881
Pulses		Yes			Mung bean	14,000	600	Yes	73	43,800	29,800	500	0	500
Cereal	Yes				Maize	15,000	1,100	Yes	18.7	20,570	5,,570	420	319	101
Fruit/vegetable		Yes			Carrot	39,000	7,500	No	20	150,000	111,000	350	0	350

Note: [a] 1 acre = 0.040685642 hectares.

d. Sensitivity analysis

		Farmer 1			Farmer 2		
FiT (INR/kWh)	Subsidy (center + state) (%)	Finger millet to arecanut (%)	Finger millet to maize-carrot (%)	Finger millet to agrivoltaics (%)	Arecanut to arecanut (%)	Arecanut to maize-potato (%)	Arecanut to agrivoltaics (%)
	30	11,722	2,002	7,348	0	-82	-37
3.5	50	11,844%	2,123	10,961	1	-81	-7
	70	11,966	2,246	14,575	2	-80	24
FiT 2	30	11,931	2,276	17,090	2	-80	45
5	50	12,053	2,399	20,703	3	-79	76
	70	12,175	2,521	24,317	4	-78	106
FiT 3	30	12,209	2,643	30,079	4	-77	155
7	50	12,331	2,766	33,693	5	-76	185
	70	12,454	2,888	37,306	6	-75	216

Anand, Gujarat

a. District profile

I. Energy constraint

Indicator 1: Source of energy	Electric	Diesel	Windmills	Solar	Manual/ animal	Others
Deep tubewell						
Medium tubewell	3,162	0	0	0	0	0
Shallow tubewell	6,664	0	0	0	0	0

Source: Fifth Minor Irrigation Census (2013-14), http://164.100.229.38/state-wise-reports?shs_term_node_tid_depth_1=81&shs_term_node_tid_depth=125

Indicator 2: Average hours of pumping/day	(a) *Kharif* season					
	0-4 hrs	4-8 hrs	8-12 hrs	12-16 hrs	16-20 hrs	20-24 hrs
Deep tubewell						
Medium tubewell	2,644	518	0	0	0	0
Shallow tubewell	4,144	2,497	23	0	0	0

Source: Fifth Minor Irrigation Census (2013-14), http://164.100.229.38/state-wise-reports?shs_term_node_tid_depth_1=81&shs_term_node_tid_depth=125

Indicator 2: Average hours of pumping/day	(b) *Rabi* season					
	0-4 hrs	4-8 hrs	8-12 hrs	12-16 hrs	16-20 hrs	20-24 hrs
Deep tubewell						
Medium tubewell	449	2151	562	0	0	0
Shallow tubewell	727	3573	2364	0	0	0

Source: Fifth Minor Irrigation Census (2013-14), http://164.100.229.38/state-wise-reports?shs_term_node_tid_depth_1=81&shs_term_node_tid_depth=125

II. Water constraint

Indicator 1: Aquifer type	Coastal Alluvium

Source: Principal Aquifers of India, CGWB, Ministry of Jal Shakti. Available at: https://cgwb.gov.in/Maps.html; accessed on 21 April 2023

Indicator 2: Distribution of tubewells based on depth	0-20 m	20-40 m	40-60 m	60-70 m	70-90 m	90-110 m	110-130 m	130-150 m	> 150 m
Deep tubewell									
Medium tubewell	0	326	1,303	1,542	0	0	0	0	0
Shallow tubewell	3,060	3,716	0	0	0	0	0	0	0

Source: Fifth Minor Irrigation Census (2013-14), http://164.100.229.38/state-wise-reports?shs_term_node_tid_depth_1=81&shs_term_node_tid_depth=125

III. Land constraint

Indicator 1: Percentage of land irrigated	82%

Source: Census 2011.

b. District crop profile to identify farmer agents

Crop	Area under cultivation (in 1000 ha)	Area irrigated (in 1000 ha)	Area under cultivation as a % of total area
Rice	88.2	88.2	41
Wheat	53.7	50.9	25
Pearl millet	28.6	28.6	13
Tobacco	15.6	15.6	7
Banana	13.5	13.5	6
Cotton	3.1	3.1	1
Citrus	5.2	5.2	2
Papaya	2.4	2.4	1
Mango	2.3	2.3	1
	212.6		

Source: https://agricoop.nic.in/sites/default/files/GUJ%2011-Anand%2030.04.2011.pdf

c. Economics and Water related data, assumptions and estimations

Crop type	*Kharif*	*Rabi*	*Zaid*	Annual	Crop	Cost of cultivation (INR/acre)[a]	Yield (kg/acre)	MSP	Price (INR/kg)	Revenue (INR/acre)	Profit(INR/acre)	Crop water requirement (mm)	Effective rainfall (mm)	Irrigation water requirement (mm)
Cereal	Yes				Rice	19,838	2,227	Yes	19.4	43,198	23,360	1,400	537	863
Cereal		Yes			Wheat	12,000	1,296	Yes	20.15	26,105	14,105	550	2	548
Cereal	Yes				Pearl	11,000	1,400	No	16.5	23,100	12,100	400	537	0
Cash	Yes				Tobacco	25,911	873	No	65	56,737	30,826	500	537	0
Fruit				Yes	Banana	125,000	12,146	No	13	157,895	32,895	1,700	540	1,160
Vegetable		Yes			Potato	39,830.83	9,700	No	9	87,300	47,469	600	2	598
Unclassified			Yes		Green	10,756.66	25,000	No	5	12,5000	114,243	1,200	540	660

Note: [a] 1 acre = 0.040685642 hecta

d. Sensitivity analysis

Sale of energy

		Farmer 1			Farmer 2		
FiT (INR/kWh)	Subsidy (center + state) (%)	Rice-wheat to banana (%)	Rice-wheat to tobacco-potato (%)	Rice-wheat to rice-wheat-fodder (%)	Tobacco-potato to banana (%)	Tobacco-potato to tobacco-potato (%)	Tobacco-potato to rice-wheat-fodder (%)
	30	163	33	317	-38	2	-1
3.5	50	182	349	337	-33	6	4
	70	201	368	356	-29	11	8
FiT 2	30	191	368	333	-31	11	3
5	50	210	387	352	-26	16	7
	70	230	406	371	-22	20	12
FiT 3	30	229	419	354	-22	23	8
7	50	249	438	373	-17	28	12
	70	268	457	392	-13	32	17

Sale of water

		Farmer 1			Farmer 2		
FiT (INR/kWh)	Subsidy (center + state) (%)	Rice-wheat to banana (%)	Rice-wheat to tobacco-potato (%)	Rice-wheat to rice-wheat-fodder (%)	Tobacco-potato to banana (%)	Tobacco-potato to tobacco-potato (%)	Tobacco-potato to rice-wheat-fodder (%)
	30	354	553	467	8	55	35
3.5	50	374	572	486	12	59	39
	70	393	591	506	17	64	44
FiT 2	30	354	553	467	8	55	35
5	50	374	572	486	12	59	39
	70	393	591	506	17	64	44
FiT 3	30	354	553	467	8	55	35
7	50	374	572	486	12	59	39
	70	393	591	506	17	64	44

Botad, Gujarat

a. District profile

I. Energy constraint

Indicator 1: Source of energy	Electric	Diesel	Windmills	Solar	Manual/ animal	Others
Deep tubewell*	-	-	-	-	-	-
Medium tubewell	496	0	0	0	0	0
Shallow tubewell	10	0	0	0	0	0
Dugwell	25,075	0	0	0	0	0

*There are no deep tubewells in Botad.
Source: Fifth Minor Irrigation Census (2013-14), http://164.100.229.38/state-wise-reports?shs_term_node_tid_depth_1=81&shs_term_node_tid_depth=125

Indicator 2: Average hours of pumping/day	(a) *Kharif* season					
	0-4 hrs	4-8 hrs	8-12 hrs	12-16 hrs	16-20 hrs	20-24 hrs
Deep tubewell	-	-	-	-	-	-
Medium tubewell	421	75	0	0	0	0
Shallow tubewell	4	6	0	0	0	0
Dugwell	19,536	5,513	25	0	0	1

*There are no deep tubewells in Botad.
Source: Fifth Minor Irrigation Census (2013-14), http://164.100.229.38/state-wise-reports?shs_term_node_tid_depth_1=81&shs_term_node_tid_depth=125

Indicator 2: Average hours of pumping/day	(b) *Rabi* season					
	0-4 hrs	4-8 hrs	8-12 hrs	12-16 hrs	16-20 hrs	20-24 hrs
Deep tubewell						
Medium tubewell	447	49	0	0	0	0
Shallow tubewell	6	4	0	0	0	0
Dugwell	2,636	22,055	382	2	0	0

Source: Fifth Minor Irrigation Census (2013-14), http://164.100.229.38/state-wise-reports?shs_term_node_tid_depth_1=81&shs_term_node_tid_depth=125

II. Water constraint

Indicator 1: Aquifer type	There is no data on this as it is a newly formed district.	Ahmednagar	Basic rocks (basalt)
	It was created on 15 August 2013 from southwestern Ahmedabad district and northwestern Bhavnagar district.	Bhavnagar	Basic rocks (basalt)

Source: Principal Aquifers of India, CGWB, Ministry of Jal Shakti. Available at: https://cgwb.gov.in/Maps.html; accessed on 21 April 2023

Indicator 2: Distribution of tubewells based on depth	0-20 m	20-40 m	40-60 m	60-70 m	70-90 m	90-110 m	110-130 m	130-150 m	> 150 m
Deep tubewell*	-	-	-	-	-	-	-	-	-
Medium tubewell	0	54	263	179	0	0	0	0	0
Shallow tubewell	0	10	0	0	0	0	0	0	0
Dugwell	20,141	5,697	0	0	0	0	0	0	0

*There are no tubewells in botad district.

Source: Fifth Minor Irrigation Census (2013-14), http://164.100.229.38/state-wise-reports?shs_term_node_tid_depth_1=81&shs_term_node_tid_depth=125

III. Land constraint

Indicator 1: Percentage of land irrigated	39.47%

Source: https://agricoop.gov.in/sites/default/files/BOTAD.pdf

b. District crop profile to identify farmer agents

Crop	Area under cultivation (in 1000 ha)	Area irrigated (in 1000 ha)	Area under cultivation as a % of total area
Cotton	167	62	79%
Wheat	17	8	8%
Sorghum	12	0	6%
Sesame	6	0	3%
Guar seed	1	0.06	0%
Pearl millet	0.7	0.7	0%
Spices	5	5	2%
Vegetables	3	3	1%
Total	211.7		

Source: https://agricoop.gov.in/sites/default/files/BOTAD.pdf

c. Economics and Water related data, assumptions and estimations

Crop type	Cash	Cereal	Cereal	Oilseed	Oilseed	Legume
Kharif	Yes		Yes	Yes	Yes	
Rabi		Yes	Yes			
Zaid			Yes			
Crop	Cotton	Wheat	Sorghum	Sesame	Groundnut	Chickpea
Cost of cultivation (INR/acre)[a]	149,645	21,792	17,500	22,552	10,763	11,250
Yield (kg/acre)	1,000	1,250	292	235	360	900
MSP	Yes	Yes	Yes	Yes	Yes	Yes
Price (INR/kg)	160	20	27	73	55	52
Revenue (INR/ acre)	160,000	25,000	7,875	17,185	19,823	46,800
Profit (INR/ acre)	10,355	3,208	-9,625	-5,367	9,060	35,550
Crop water requirement (mm)	1,000	550	550	600	450	430
Effective rainfall (mm)	779	0	0	779	0	0
Irrigation water requirement (mm)	221	550	550	0	450	430

Note: [a] 1 acre = 0.040685642 hectares.

d. Sensitivity analysis

		Farmer 1		
FiT (INR/kWh)	Subsidy (centre + state) %	Cotton-groundnut to groundnut-sesame (%)	Cotton-groundnut to cotton-groundnut (%)	Cotton-groundnut to groundnut-wheat (%)
	30	14	-36	-97
3.5	50	51	1	-60
	70	88	38	-23
FiT 2	30	92	36	-36
5	50	129	73	1
	70	166	110	38
FiT 3	30	196	131	46
7	50	233	168	83
	70	270	206	120

Nadia, West Bengal

a. District profile

I. Energy constraint

Indicator 1: Source of energy	Electric	Diesel	Windmills	Solar	Manual/ animal	Others
Deep tubewell	513	392	0	0	0	4
Medium tubewell	168	136	0	0	0	2
Shallow tubewell	2,812	74,685	34	5	0	117

Source: Fifth Minor Irrigation Census (2013-14), http://164.100.229.38/state-wise-reports?shs_term_node_tid_depth_1=81&shs_term_node_tid_depth=125

Indicator 2: Average hours of pumping/day	(a) *Kharif* season					
	0-4 hrs	4-8 hrs	8-12 hrs	12-16 hrs	16-20 hrs	20-24 hrs
Deep tubewell	389	137	243	134	10	6
Medium tubewell	77	171	39	26	4	1
Shallow tubewell	28,181	38,265	10,425	1,023	399	181

Source: Fifth Minor Irrigation Census (2013-14), http://164.100.229.38/state-wise-reports?shs_term_node_tid_depth_1=81&shs_term_node_tid_depth=125

Indicator 2: Average hours of pumping/day	(b) *Rabi* season					
	0-4 hrs	4-8 hrs	8-12 hrs	12-16 hrs	16-20 hrs	20-24 hrs
Deep tubewell	362	231	206	84	32	4
Medium tubewell	63	99	114	39	3	0
Shallow tubewell	20,555	38,618	15,611	2,897	612	181

Source: Fifth Minor Irrigation Census (2013-14), http://164.100.229.38/state-wise-reports?shs_term_node_tid_depth_1=81&shs_term_node_tid_depth=125

II. Water constraint

Indicator 1: Aquifer type	Laterite / Ferruginous concretions

Source: Principal Aquifers of India, CGWB, Ministry of Jal Shakti. Available at: https://cgwb.gov.in/Maps.html; accessed on 21 April 2023

Indicator 2: Distribution of tubewells based on depth	0-20 m	20-40 m	40-60 m	60-70 m	70-90 m	90-110 m	110-130 m	130-150 m	> 150 m
Deep tubewell	0	0	0	0	438	87	218	33	147
Medium tubewell	0	24	185	109	0	0	0	0	0
Shallow tubewell	42,581	37,922	0	0	0	0	0	0	0

Source: Fifth Minor Irrigation Census (2013-14), http://164.100.229.38/state-wise-reports?shs_term_node_tid_depth_1=81&shs_term_node_tid_depth=125

III. Land constraint

Indicator 1: Percentage of land irrigated	61.50%	Likely to be much higher, given that much of West Bengal is completely electrified

Source: Census 2011.

b. District crop profile to identify farmer agents

Crop	Area under cultivation (in 1000 ha)	Area irrigated (in 1000 ha)	Area under cultivation as a % of total area
Rice	243		43
Vegetables	91		16
Rapeseed and mustard	88		16
Minor pulses	62		11
Sesame	29		5
Fruits	23		4
Maize	6		1
Potato	5		1
Groundnut	4		1
Chickpea	3		1
Sugarcane	2		0
Fodder	1		0
Pigeonpea	0		0
Sunflower	0		0
Total	558		

Source: http://data.icrisat.org/dld/src/crops.html

c. Economics and Water related data, assumptions and estimations

Crop type	*Kharif*	*Rabi*	*Zaid*	Annual	Crop	Cost of cultivation (INR/acre)[a]	Yield (kg/acre)	MSP	Price (INR/ kg)	Revenue (INR /acre)	Profit (INR/ acre)	Crop water requirement (mm)	Effective rainfall (mm)	Irrigation water requirement (mm)
Cereal	Yes				Rice - Aus	16,667	1,000	Yes	19.4	19,400	2,733	1,400	1,057	343
Cereal		Yes			Rice - Boro	16,667	1,000	Yes	19.4	1,9400	2,733	1,400	161	1,239
Cereal			Yes		Rice - Aaman	16,667	1,000	Yes	19.4	19,400	2,733	1,400	4	1,396
Vegetable	Yes	Yes	Yes		Potato	100,000	10,500	No	15	157,500	57,500	450	161	289
Oilseed		Yes			Mustard	9,493	600	Yes	50.5	30,300	20,807	400	4	396
Pulses		Yes			Lentil	15,000	600	Yes	55	33,000	18,000	500	4	496
Oilseed	Yes				Sesame	15,375	225	Yes	73	16,425	1,050	600	1,057	0
Fruit				Yes	Mango	270,000	7,000	No	100	700,000	430,000	600	1,207	0

Note: [a] 1 acre = 0.4046 hectares.

d. Sensitivity analysis

		Farmer 1		
FiT (INR/kWh)	Subsidy (center + state) (%)	Aus-Aaman-Boro to Aus-Aaman-Boro (%)	Aus-Aaman-Boro to Aus-lentils (%)	Aus-Aaman-Boro to Aus-lentils-potato (%)
None		-105	15	899
	30			
3.5	50			
	70			
FiT 2	30			
5	50			
	70			
FiT 3	30			
7	50			
	70			

Energy-related assumptions and estimations for all case studies

S. no.	Parameters	Estimated/assumed	Values
a	Pump capacity (hp)[a]	Assumed	10
b	Conversion factor (to estimate solar panel capacity)	Assumed	1.2
c	Equivalent solar panel capacity (hp)	Estimated (a×b)	12
d	Hp to wattage (W) conversion factor	Assumed	0.75
e	Power required (kw)	Estimated (c×d)	9
f	Panel rating (wattage)	Assumed	400
g	Number of panels	Estimated ((e×1000)/f)	23
h	Number of hours of sunlight	Assumed	6
i	Number of days in a year	Assumed	300
j	Total energy generated (kwh or units)	Estimated ((e×h*i) ×0.8)	12,960
k	Energy used for irrigation (kwh or units)	Estimated (sum of IWR of crops chosen) ×e	
l	Energy available to sell back to the grid	Estimated (j-k)	
m	Reduction in energy generated in the 1st year	Assumed	0.99%
n	Reduction in energy generated from 2nd to 25th year	Assumed	0.96%
o	System costs (INR/wattpeak)	Assumed	40
p	Capital costs (INR)	Estimated (o×e×1000)	360,00 0
q	O&M costs/year (%)	Assumed	10%
r	O&M costs/year (INR)	Estimated (q×p)	36,000
	Revenue/year	Estimated (FiT×l)	

Farmer Responses to Solar Irrigation in India Agent-Based Modeling to Understand Sustainable Transitions
WELL Labs

Submitted to
International Water Management Institute